A COST-BENEFIT ANALYSIS OF TSETSE CONTROL IN TANZANIA

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ABSTRACT

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African trypanosomiasis is endemic in sub-Saharan Africa and most frequently affects the rural poor and their livestock. The financial resources for controlling tsetse fly, the primary vector of the disease, have been reduced since the 1970s. The decrease in funding has partially resulted from the dissatisfaction of donors on the limited benefits from large investment on tsetse control campaign. To analyze the cost-benefit balance of the tsetse control campaigns in Tanzania, this study adopts McCord et al's (2012) methods to calculate the control costs based on the spatially and temporally constrained fly distributions, termed control reservoirs. The benefit of tsetse fly management is evaluated based on the unevenly distributed population densities in Tanzania. The control activities in tsetse habitats with large population density can maximize the control benefits through the maximum reduction of exposure potential. Therefore, the highly populated areas with frequent presence of the tsetse flies are defined as beneficial control areas (BCAs), which are the places with over 52% tsetse presence and population densities over 1,000 per km^2 in this study. The result shows 484 1km*1km BCAs identified in Tanzania with the second-order clustering patterns. This study helps to improve the cost-benefit equation for broad tsetse control campaigns and disease management.

To my parents,
For supporting and encouraging me to believe in myself

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TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

KEY TO ABBREVIATIONS

AAT	African Animal Trypanosomiasis
ADB	African Development Bank
AU	African Union
AU-IBAR	African Union Inter-African Bureau for Animal Resources
BCA	Beneficial Control Area
CDC	Centers for Disease Control and Prevention
CF	Sleeping Sickness Active Case Finding
CR	Control Reservoir
DDT	Dichloro-Diphenyl-Trichloroethane
EA	Environmental Impact Assessment
EE	Environmental and Entomological Monitoring
ET	Entomological Survey and Tsetse Fly Population Genetics Surveying
FAO	Food and Agriculture Organization
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
HIV / AIDS	Human Immunodeficiency Virus Infection and Acquired Immune Deficiency Syndrome

HAT	Human African Trypanosomiasis
IAEA	International Atomic Energy Agency
ICZ	Intertropical Convergence Zone
ILRI	International Livestock Research Institute
NDVI	Normalized Difference Vegetation Index
OAU/ISCTRC	Organization of African Union / International Scientific Council for Trypanosomiasis Research and Control
PATTEC	Pan-African Tsetse and Trypanosomiasis Eradication Campaign
PCV	Packed Cell Volume
PS	Parasitological and Serological Data Collection
ROI	Return on Investment
SE	Socioeconomic Survey
SIT	Sterile Insect Technique
SS	Sleeping Sickness Survey
TED Model	Tsetse Ecological Distribution Model
TZ	Tsetse Zone
USAID	United States Agency for International Development
WHO	World Health Organization
WWII	World War II

CHAPTER 1

TRYPANOSOMIASIS, TSETSE FLY, AND POPULATION IN TANZANIA

1.1 Introduction

Trypanosomiasis is a vector-borne disease cyclically transmitted by the tsetse fly. This disease is caused by the trypanosoma protozoa and is better known as sleeping sickness in humans and *nagana* in animals (DeVisser, 2009). Trypanosomiasis is endemic in more than 37 countries in sub-Saharan areas and most frequently affects the rural poor and their livestock. For the human disease, there were three major epidemics in Africa over the last century: one between 1896 and 1906, and the other two in the 1920s and 1970s (WHO, 2016). In the first epidemic, the most serious one, it was estimated that about 70 million people were at risk of sleeping sickness and resulted in 300,000 to 500,000 reported deaths (Steverding 2008; WHO, 2016). After continuous control efforts, the number of reported new cases declined dramatically to 3,796 in Africa in 2014 (WHO, 2016). However, with more concerns devoted to other diseases (e.g. Malaria, Ebola, Tuberculosis, HIV / AIDS) during the past 20 years, sleeping sickness is now classified as a neglected tropical disease (Yamey, 2002; Malele, 2012; WHO, 2016). Many cases are undiagnosed or untreated, and therefore not reported. This indicates that the actual infection rate should be higher (CDC, 2008a/2008b; WHO, 2016).

African Animal Trypanosomiasis poses a risk to 46 million domestic animals in Africa (Swallow, 2000). Animal trypanosomiasis affects the agricultural development and the

African economy by directly influencing livestock production. For the tsetse-infested areas in Africa, animal trypanosomiasis reduced the meat and dairy production by at least 50% (Swallow, 1999; Magez and Radwanska, 2014). Besides, poor livestock health, as a result of the disease, also has an indirect impact on crop yields and areas cultivated, in terms of the manure and animal traction (Kilemwa, 1999; Swallow, 1999).

Given the public health issue and economic burdens imposed by trypanosomiasis, tsetse control campaigns have long been attempted to eliminate the vector (Hargrove, 2003). During the colonial period in Africa, early tsetse control practices included wild animal removal, population evacuation, and tsetse habitat destruction (Knight, 1971; Yorke, 1913; Hargrove, 2003). After the World War II, some contemporary control methods to control tsetse fly have been introduced, such as insecticide spraying, sterile insect technique, and insecticide-treated cattle (King and Crews, 2013). Detailed applications and efforts of these contemporary control methods as applied in Tanzania will be described in Chapter 2. Despite the long-term control of the tsetse fly, the elimination of tsetse flies has failed partly due to the limited financial resources, tsetse reinvasion problems, poor coordination among countries, and environmental concerns (Hargrove, 2000; Hargrove and Vale, 2005). The reduction of control funding since the 1970s has been the result of the decreasing donor support because of the failure of previous large investments in tsetse control (Hargrove, 2002; McCord, 2011). This study addresses the cost-benefit balance for broad control campaigns by exploring the cost implications for vector management and identifying the most beneficial control areas based on the exposure potential in Tanzania.

1.2 Disease, Tsetse Fly, and Population Exposure in Tanzania

1.2.1 Geography, Tsetse Ecology and Trypanosomiasis in Tanzania

Tanzania lies in East Africa, within the African Great Lakes region. It occupies 945,203 square kilometers, and is bordered by the Indian Ocean to the east; Kenya and Uganda to the north; Rwanda, Burundi, and the Republic of Congo to the west; Zambia, Malawi, and Mozambique to the south. Mount Kilimanjaro in northeastern Tanzania is the highest mountain in Africa at 5,895 meters above sea level (Agrawala et al., 2003). Lake Victoria covering 69,490 square kilometers is Africa's largest lake, 49% of which lies in Tanzania. It is important to note that the focus area in this study is mainland Tanzania, excluding the Mafia Island, Pemba Island, and Zanzibar (See Figure 1.1).

The climate varies considerably within Tanzania. The temperature of the hottest period occurring between November and February ranges from 25 °C to 31 °C, while that of the coldest period extends from May to August and ranges from 15 °C to 20 °C (Kasuka, 2013). Since the country is located just south of the equator, the annual temperature for most areas is above 20 °C.

There are two major rainfall regimes in Tanzania: uni-modal (April-October) and bi-modal (October-December and March-May) (Zorita and Tilya, 2002). The uni-modal regime influences the southern, western and central Tanzania. The bi-modal regime produced by the seasonal migration of the Intertropical Convergence Zone (ICZ) is found in the north extending from Lake Victoria to the eastern coast (Zorita and Tilya, 2002). The main rainy season (the "long rains") in Tanzania lasts from March to May. Another rainy season called the “short rains” starts in November and ends in December (Camberlin and Philippon, 2002). The “long rains” period usually has more rainfall events and lower inter-annual variability than “short rains” (Camberlin and Okoola, 2003). The “long dry season” when rainfall is not usual spans from June to October (Prins and Loth, 1988). The “short dry season” is generally in January and February.

Figure 1.1: Study Area. *This figure shows geographic location and the first-level administrative divisions (regions) of Tanzania*

The tsetse fly (genus *Glossina*) is a k-strategist insect with relatively low fecundity and mortality rates (Rio et al., 2006). Tsetse survival depends on the availability of ecological niche including temperature, moisture, and land covers (Pollock 1982 b, Leak 1999). Regarding the climate conditions, tsetse flies are usually found in areas with a mean yearly temperature between 19-28 °C (Pollock, 1982b). The fly population usually thrive when temperatures ranges from 21°C to 26°C (Pollock, 1982b, DeVisser, 2009). However, temperatures above 40 °C or below 10 °C are lethal to their survial (Knight, 1971; Torr and Hargrove, 1999; Terblanche et al., 2008). Also, moisture is another essential climate condition for the survival of tsetse flies. The low moisture levels have an adverse impact on the fly population (Nash, 1933). The optimum saturation deficits of moisture range from 6.0 to 17.3 hPa (Rogers, 1979; DeVisser et al., 2010). In order to prevent possible desiccation, tsetse flies pass most of their time hiding in the shaded places in particular woody vegetation land covers (Leak, Ejigu, and Vreysen, 2008). The preferred woody vegetation is defined as a woody plant with a diameter of 1-3cm, a height of 1-4 meters and a coarse surface (Austenand and Hegh, 1922; Jordan, 1986; DeVesser et al., 2010). The tsetse flies prefer to rest in the holes between the roots or around the trunks (Pollock, 1982b). The components of tsetse ecology show in Figure 1.2. The overlap of the three components is tsetse ecology. Currently, there are 22 different species of tsetse fly in Africa, which are divided into three species groups: *Morsitans* group, *Palpalis* group and *Fusca* group (Pollock, 1982a; Moloo, 1993; Rayaisse et al., 2011). *Morsitans* group, known as “savannah” subgenus, have a wide range of mammalian host species and prefer to live in the savannah (grassy woodland)

(Moloo, 1993; Pollock,1982a; Cecchi et al., 2008). They are also found in scattered thickets and forest edges (Cecchi et al., 2008). *Palpalis* group, known as "riverine" subgenus, are found in humid areas in Africa, such as the gallery forest, swamps, and riparian canopy (Pollock, 1982a; Moloo, 1993; Tanekou et al., 2011). *Fusca* group are the forest flies inhabiting forests of west, central and east Africa (Pollock, 1982a; Cecchi et al., 2008). There are eight species of tsetse fly living in Tanzania: *Morsitans* group, the most widely distributed group in the country includes four species, *Glossina morsitans, G. austeni*, *G. pallidipes* and *G. swynnertoni*; *Fusca* group in Tanzania has *G. longipennis*, *G.brevipalpis*, and *G.fuscipleuris*; *Palpalis* group only includes one species *G. fuscipes* (Pollock, 1982a; Malele, Nyingilili, and Msangi, 2011).

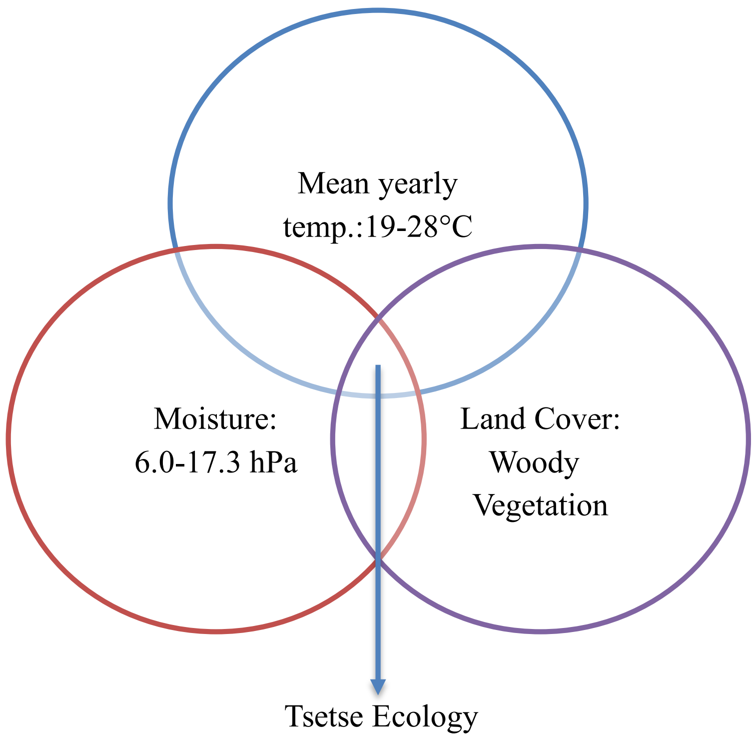


Figure 1.2: Tsetse ecology. *The components of tsetse ecology are shown in figure*

Human African trypanosomiasis is endemic in 9 regions in Tanzania, namely Arusha, Kagera, Manyara, Mara, Lindi, Mbeya, Rukwa, Ruvuma, and Tabora region, shown as highlighted regions in brown in Figure 1.1 (Kibona, Nkya and Matemba, 2004). Although the reported cases across Africa dropped by 73.4% during the recent decade, 300 new cases of human trypanosomiasis are reported annually in Tanzania recently (WHO, 2016; Malele, 2012). Compared to human trypanosomiasis, animal trypanosomiasis is much more widely distributed in Tanzania. In 1975, it was reported that 12,098,000 cattle, 7,160,000 small ruminants, 161,000 equines, and 23,000 swine were at risk of the disease (USAID, 1980). Presently, despite the control campaigns, there is still around 4.4 million livestock under risk of animal trypanosomiasis in Tanzania (Malele, 2012).

1.2.2 Population and Economy in Tanzania

The population of Tanzania in 2015 was reported at approximately 51.82 million. The population distribution in the country is extremely uneven, and the population densities vary from 12 to 3,133 per square kilometer. Most people live along the eastern coast and at the northern part of the country, while the rest is sparsely populated (Marco and Mlay, 1979). With around 70 percent rural population, the economy of Tanzania is heavily dependent on agriculture. As the mainstay of Tanzania's economy, agriculture contributed to 24.5 percent of gross domestic product (GDP), provided 85 percent of exports, and accounted for over 80 percent of the employed workforce in 2013 (NBS, 2013; ITC, 2014). Although the GDP of Tanzania has grown impressively over the past decade, the country still remains as one of the poorest countries in the world, regarding per capita income (Ellis and Mdoe, 2003; Mbatia and Jenkins, 2010). People whose main source of incomes is farming or livestock are five times more likely to be poor than those employed in other sectors (Narayan-Parker, 1997). Poverty in Tanzania is a typically rural phenomenon: over 69 percent of poor people live in rural areas in 2014 (World Bank, 2016).

1.3 The Statement of Problem

Limited financial resources have been the main impediment of previous tsetse control practices (Rogers and Randilph, 2002; Shaw, 2007). Beginning from the 1970s, the funding sources for broad control campaigns have been reduced by governments and donor groups (Hargrove, 2000; Hargrove, 2003). In addition, among the thirty-seven tsetse infested countries in Africa, thirty-two of them are regarded as heavily indebted poor countries (Feldmann et al., 2005). It is quite hard for these countries to obtain the funding for tsetse control, and Tanzania is among one of them. With two-thirds of the country occupied by tsetse flies, the expense for tsetse eradication is simply unaffordable for the Tanzanian government.

Moreover, the reduced funding from donors since the 1970s was partly due to the donors' dissatisfaction with the results of previous tsetse control campaigns (Hargrove, 2002; McCord, 2011). Balancing the socioeconomic effects and tsetse control budgets is another challenge for the fly management. Given the unevenly distributed population in Tanzania, population equity issue arises with the differential and political application of tsetse control. The limited control benefits in some areas with low human and livestock populations cannot cover the costs for tsetse fly management (Shaw, 1986). Therefore, even under the assumption that the country could afford the control costs, the benefits to control the disease should still be evaluated in the context of return on investment (ROI).

1.4 Purpose of Study

1.4.1 Study Objectives

The goal of my thesis research is to conduct a cost-benefit analysis of the tsetse control campaigns to identify the places where the control benefit can be maximized by the maximum reduction of exposure potential to balance the control cost in Tanzania.

The objectives of my thesis are:

(1) To identify the spatiotemporal distributions of tsetse flies in Tanzania;

(2) To explore the cost implications for vector management in Tanzania by maximizing the limited financial resources based on the seasonal variations of tsetse distributions;

(3) To improve the cost-benefit equation by analyzing the spatial relationship between tsetse distribution and exposure potential of the disease.

1.4.2 Research Hypothesis

Following the objectives, I hypothesize that: (1) There are seasonal variations among the dynamic distributions of tsetse fly in Tanzania; (2) The control costs can be managed for ROI by considering the spatiotemporal variability in tsetse control management; (3) The ROI for tsetse control can be measured by studying the spatial relationship of tsetse and human habitats.

CHAPTER 2

LITERATURE REVIEW

2.1 Transmission Cycles

Trypanosomiasis is caused by the protozoa *trypanosoma* and cyclically transmitted by the tsetse fly vector (Mulligan and Potts, 1970; Hoare, 1972; Leak 1999). Trypanosomes have a complex life cycle with differentiated biological stages inside the tsetse fly and diverse hosts (Magez and Radwanska, 2014; Franco et al., 2015). The cycle in the fly takes approximately 3 weeks. A healthy tsetse fly can become infected with trypomastigotes when taking a blood meal from an infected mammalian host (Austen, 1903; Magez and Radwanska, 2014). The trypomastigotes transform into procyclic trypomastigotes and multiply by binary fission in the fly's midgut (Barrett and Stanberry, 2009; CDC, 2015). After leaving the midgut, the procyclic trypomastigotes transform into epimastigotes and continue multiplication in the fly's salivary glands (Barrett and Stanberry, 2009; CDC, 2015). Finally, they transform into metacyclic trypomastigotes. When an infected tsetse fly takes the blood meal from the mammalian host, the metacyclic trypomastigotes are injected into the skin tissue of the hosts (Magez and Radwanska, 2014; CDC, 2015). The parasites first enter the lymphatic system and then pass through the bloodstream (CDC, 2015). Inside the body of the host, they transform to bloodstream trypomastigotes, reach other sites of the body, and continue replication by binary fission (CDC, 2015). Hosts are usually preferentially selected by the tsetse fly: 1) hosts appear at tsetse-infested areas; 2) the smell or sight of the hosts is very attractive to the fly, like cattle; 3) hosts remain undisturbed by feeding tsetse flies, especially when distracted by eating or drinking (Pollock, 1992b).

The transmission cycle is shown in Figure 2.1. Most tsetse-transmitted trypanosomes occur in animal systems with asymptomatic results, but for non-resistant animals, the trypanosomes cause African Animal Trypanosomiasis (AAT) (Steverding, 2008; CFSPH, 2009). More than 30 species of the wild animals have been described as maintenance hosts. These include giraffe, bushbuck, warthog, reptiles, hippopotamus and porcupine. (Pollock, 1992b; Leak, 1999). Curiously, there are some wild animals not fed upon by tsetse flies under typical conditions, including zebra, wildebeest, and many small antelopes, the reasons for which are not fully understood (Pollock, 1992b).

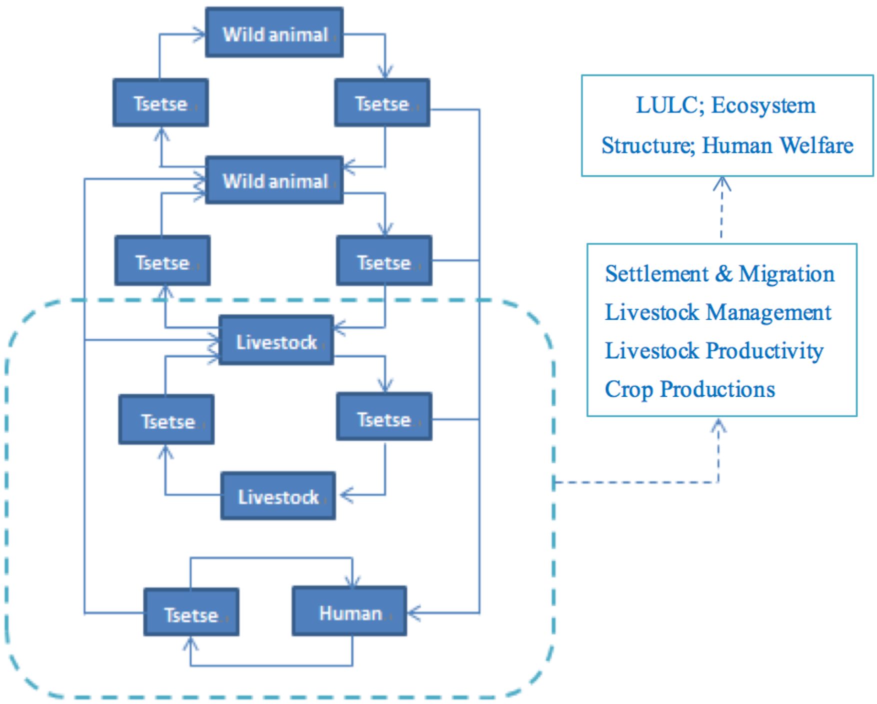


Figure 2.1: Transmission cycles. *The transmission cycle and the outcomes of trypanosomiasis are shown in this figure*

Trypanosoma can also be transmitted between livestock and game animals, when livestock come into close proximity with bush-dwelling wild animals. Various scenarios where wild animals and livestock interact have been proposed including, 1) wild animals excurse into residential areas where domestic animals are kept, or domestic animals roam into forests, 2) wild animals might appear when the herds are left untended for a long period or allowed to wander freely 3) the grazing areas of some wild animals and livestock overlap (Buxton, 1955; Allsopp, 1972; WHO, 2013). Trypanosomes can infect most livestock with clinical cases reported in cattle, water buffalo, sheep, goats, camels, horses, donkeys, alpacas, llamas, pigs, dogs, cats, also among many others (Spickler, 2010). Due to the observed feeding preferences of the tsetse fly, cattle are the most frequently affected livestock by the trypanosomiasis (Spickler, 2010).

The transmission of human African trypanosomiasis (sleeping sickness) generally occurs in rural areas of subsistence agriculture or pastoralism (WHO, 2016). Sleeping sickness has two forms, depending on the parasites involved, either *Trypanosoma brucei gambiense* or *Trypanosoma brucei rhodesiense* (Simarro et al., 2008).

The transmission cycles of *gambiense* sleeping sickness and *rhodesiense* sleeping sickness are different. The transmission cycle of *rhodesiense* sleeping sickness involves a wide range of wild and domestic animals (Enyaru et al., 2006). Since animals act as the reservoir hosts, *T. b. rhodesiense* is usually transmitted directly from animals to humans by the tsetse fly (Cook and Zumla, 2008). In the cases when wild animals serve as reservoirs, the transmission of the disease is associated with the contact between human and wild animal reservoirs. *T. b. rhodesiense* can be transmitted to humans directly from wild animals through the tsetse fly. This usually happens when humans stepped into protected areas or forests frequented by the fly. One typical example is the increasing reported HAT cases for visitors or tourists in the national parks (Migchelsen et al., 2011). Also, the tsetse fly can transmit *rhodesiense* sleeping sickness to humans indirectly from wild animals, passing the disease through livestock (Franco et al. 2014). This could occur especially when the grazing areas of livestock overlap those of wild animals due to the land-use pressure (Simarro et al., 2010; WHO, 2013). In the cases when many livestock are infected and act as the main reservoirs inside the tsetse habitats, the outbreaks of the animal-fly-human transmission can easily occur in the intersection of the presence of humans, livestock and tsetse fly (Franco et al., 2014). *Rhodesiense* sleeping sickness causes an acute infection leading to death within several weeks or months. The intensified human-fly-human transmission is very unlikely and may only occur in the epidemics (Simarro et al., 2008; WHO, 2016).

For *T. b. gambiense*, humans are the primary reservoirs, thus the human-fly-human transmission of *gambiense* sleeping sickness is the most common form (Pépin and Méda, 2001; Franco et al., 2014; WHO, 2016). Although some animals can also harbor the parasite, the animal-fly-human transmission cycle only occasionally occurs (Burn et al., 2010). Some studies related the prevalence of *gambiense* trypanosomiasis in wild animals to that of *gambiense* sleeping sickness, and suggested that wild fauna could serve as a possible animal reservoir (Njiokou et al., 2006). Additionally, domestic animals were also reported as reservoirs for *gambiense* sleeping sickness, because the same parasite has been found in domestic animals (mainly pigs) in some *gambiense* human foci (Njiokou et al., 2010). The role played as reservoirs by pigs in the transmission of *gambiense* sleeping sickness was suspected by some researchers (Franco et al., 2014). Some studies showed the parasite was not found in livestock in some foci where the infection is common in humans (Balyeidhusa, Kironde, and Enyaru, 2012). Other studies showed that the infection rate and genotypes of the *T. b. gambiense* parasites in humans and livestock were different, which suggested that these livestock may not act as reservoirs for humans (Jamonneau et al., 2004). Therefore, more researches are needed to clarify the actual role the animal reservoirs play in the transmission of *gambiense* sleeping sickness (WHO, 2013; Franco et al. 2015).

2.2 Control Motivation

Tsetse and trypanosomiasis have a disproportionate impact on the rural poor and their livestock, who live in the area prone to higher presence of tsetse and therefore a higher rates of disease (Scoones, 2014). Tsetse and trypanosomiasis control has been historically conducted by the African government. The overall political motivation of government-led tsetse control operations was to reduce the impact of tsetse flies and trypanosomiasis on humans and domestic animals (Agyemang, 2005).

2.2.1 Control Motivation for Trypanosomiasis in Africa

African Animal Trypanosomiasis (AAT) greatly affects food production and the natural-resource utilization, so that this disease is regarded as one of the most ubiquitous and significant constraints to agricultural development throughout much of sub-Saharan Africa (Hursey and Slingenbergh, 1995; ADB, 2004). Animal trypanosomiasis causes countless deaths of livestock annually, thus directly lowers birth rates of livestock, milk and meat yields (Maudlin, Holmes and Miles, 2004; Jordan, 1985). In endemic areas, it was estimated that about 48 million cattle were at risk of contracting trypanosomiasis, which causes annual deaths of about 3 million (Hursey and Slingenbergh, 1995; Ilemobade, 2009). For the direct production in cattle, the yearly losses ranged from $ 1 billion (USD) to $ 1.2 billion (USD) (Hursey and Slingenbergh, 1995; Ilemobade, 2009).

Additionally, animal trypanosomiasis also has the indirect impact on crop production in terms of the availability and health of livestock for animal traction (Jordan, 1985; Swallow, 1999). With additional traction available, it could allow farmers to expand their cultivated areas, increase crop yields, and allocate labors more efficiently (Swallow, 1999). There are some other ways that livestock interact with the crop production, including the cycling of nutrients through livestock, feeding livestock with crop residues, and competition between livestock and crops for available lands (Swallow, 1999). All told, this disease impacts Africa's economic development by limiting the total annual agricultural income to $ 4.5 billion (USD) below potential (FAO, 2008).

As one of the important public health issues, human African trypanosomiasis is another motivator for the government to control tsetse flies. There are two forms of sleeping sickness: *gambiense* sleeping sickness and *rhodesiense* sleeping sickness, as previously described. *Gambiense* sleeping sickness affects 24 countries in west and central Africa (WHO, 2016). This form causes a chronic infection: the person may not show any major signs or symptoms of the disease for months or years after the infection (Picozzi et al.,2005). *Gambiense* sleeping sickness is estimated to account for about 98% of reported cases (WHO, 2016). However, the *rhodesiense* sleeping sickness is reported in 13 countries in east Africa (WHO, 2016). This form causes an acute infection: the infected person usually shows the first signs and symptoms in a few weeks or months (WHO, 2016). Based on the reported cases, the spatial distributions of two types of the trypanosomes and trypanosomiasis are shown in the following figure (Figure 2.2):

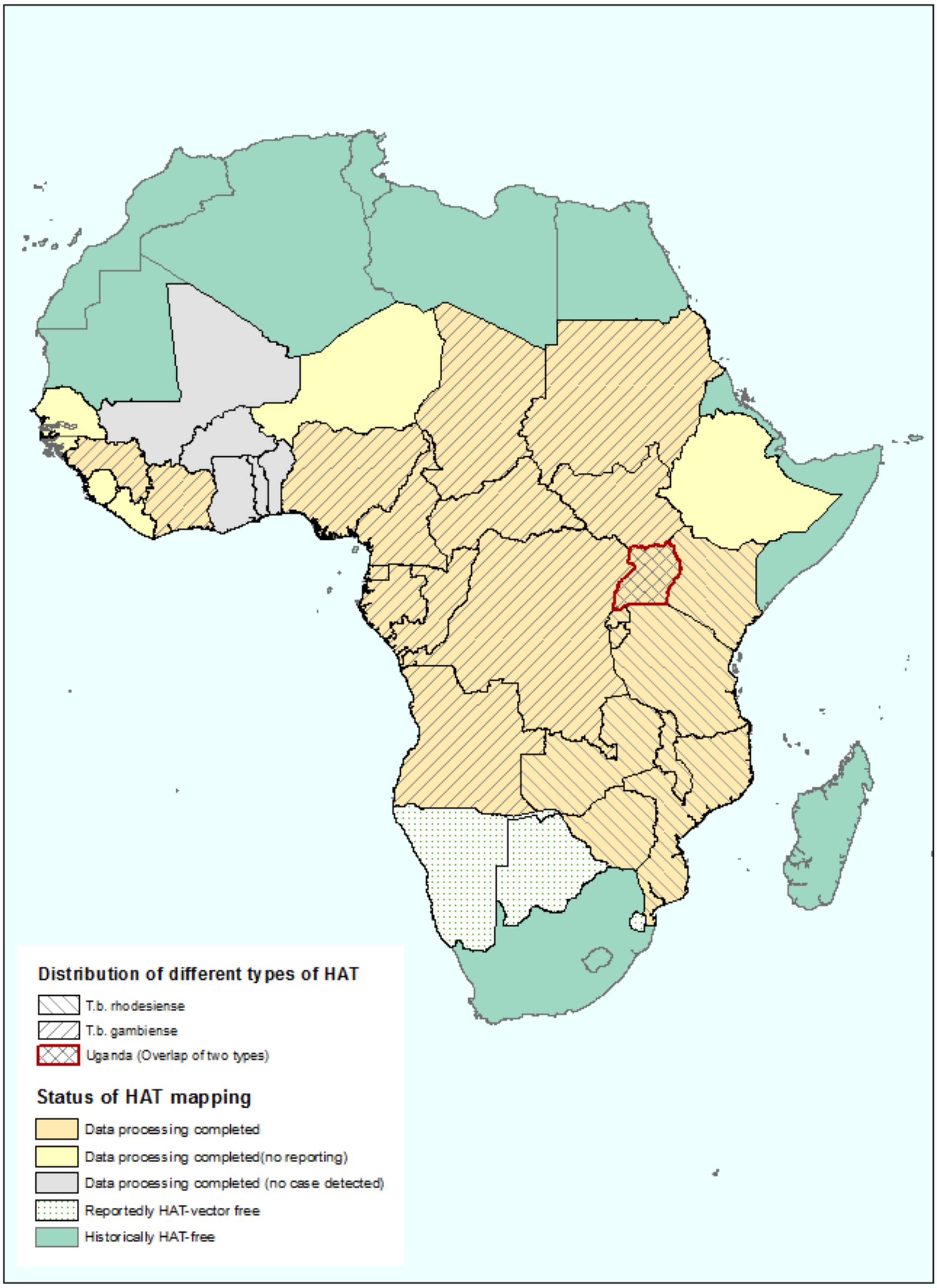


Figure 2.2: Sleeping sickness distribution. *The distribution of gambiense and rhodesiense sleeping sickness in sub-Saharan Africa from 2000 to 2009 is shown in map (Adopted from WHO, 2013)*

The infestation of tsetse flies used to influence the pattern of migration and human settlement in the past few decades (Hursey and Slingenbergh, 1995). People usually abandoned settlements and moved, due to the frequent presence of tsetse flies (Malele, 2012). The depopulation and the lack of farming activities in the abandoned areas caused the expansion of bushes and woody areas that were suitable for tsetse flies (Reid et al., 2000). Currently, with the long-term control of tsetse flies, human trypanosomiasis usually affects poor populations living in discrete rural foci (ADB, 2004). This disease can not only cost the households in terms of treatment and time to take care of the patients, but also partly act as a contributor to disability within tsetse-infested areas (Malele, 2012; Grady et al., 2011).

The number of new cases of the human trypanosomiasis has rapidly dropped from 38,000 in 1998 to 3,796 in 2014 in Africa (WHO, 201). However, there are still about 65 million people at risk of getting the infection and an estimation of 20,000 actual cases (WHO, 2016).

2.2.2 Control Motivation for Trypanosomiasis in Tanzania

In mainland Tanzania, about two-thirds of lands are distributed among fly belts, mainly in coastal areas and the African Great Lakes regions (OAU/ISTRC, 1997). It was estimated that about 40% of lands suitable for agriculture or grazing are currently tsetse-infested and affected by trypanosomiasis, including Arusha, Kagera, Kigoma, Kilimanjaro, Manyara, Mara, Rukwa, Tabora, and Tanga regions (See Figure 1.1) (Malele, 2012). With approximately 4.4 million domestic animals at risk of animal trypanosomiasis in Tanzania, annual losses around $7.98 million (USD) are incurred on the livestock industry due to low fertility rate, mortality, and milk yield (Shaw, 2003; Malele, 2012).

There are over 4 million people estimated at risk of getting the infection in Tanzania (MoH, 2005a; Malele, 2012). The number of reported new cases has dropped to about 300 per year in the country (MoH, 2005a; Malele, 2012). However, this yearly reported cases for sleeping sickness may not reflect the actual situation. First, sleeping sickness is a neglected problem of poor rural people, thus the reported cases are likely to be underestimated (Engels and Savioli, 2006). Second, the disease sometimes is symptomatically confused with other disease, such as HIV/AIDS, tuberculosis, and Malaria (Malele et al., 2006; Malele, 2012).

2.3 Tsetse and Trypanosomiasis Control in Tanzania after Independence

Contemporary tsetse control methods implemented in Tanzania include insecticide spraying, the sterile insect technique (SIT), traps and targets, insecticide-treated cattle (ITC), and eradication campaigns (Tarimo et al., 1971 a,b; Williamson et al., 1983; Daffa, Njau, and Mwambembe, 2003; Malele, 2012).

2.3.1 Insecticide Spraying

Insecticide started to be used against tsetse flies after World War II (De Raadt P, 2005). Application of insecticides initially occurred as ground spraying and later aerial spraying (Allsopp, 2001). Control campaigns using ground spraying usually required large, well-trained teams. These people equipped with pressurized or non-pressurized sprayers were dispatched to tsetse-infested areas and sprayed the insecticide on the vegetation frequented by the fly (King and Crews, 2013). However, given the low efficiency and dependence on a large amount of well-trained laborers, ground spraying was gradually replaced by aerial spraying and is infrequently used now (Hargrove, 2003). Aerial spraying of DDT was widely used to reduce the tsetse population in the area of Babati, Arusha Region in Tanzania (Tarimo et al., 1971a, b; Tarimo, 1974). It eradicated *G. pallidipes* successfully and decreased *G. morsitans* and *G.swynnertoni* population substantially (Tarimo et al., 1971a,b). However, the high cost, environmental concerns, and poor cooperation among countries has limited the success of using aerial spraying (PATTEC, 2001).

There are also some common drawbacks for both of the insecticide spraying methods. First, insecticide spraying rarely kills the puparia of tsetse, since the puparia are buried in the soil. Insecticide spraying can only succeed either by using the lethal dose (residual insecticides) which could last long enough to control the adult tsetse after they emerge from pupa, like endosulfan and DDT, or by the reuse of non-residual insecticides, such as pyrethroid compounds (Hargrove, 2003; McCord, 2011; Malele, 2012). Second, tsetse reinvasion is an important concern for any control activities, especially when the barriers are used (Muzari and Hargrove, 1996). Therefore, it is necessary to have a systematic management for insecticide spraying from one place to another to avoid tsetse reinvasion.

2.3.2 Sterile Insect Technique (SIT)

The Sterile Insect Technique uses radiation to sterilize the male flies reducing the fertility of the tsetse population. The mating of the sterile male with the fertile female fly hinders the female from producing offspring (Malele, 2012). Once the female flies are mated, they will rarely mate with other males during the course of their lives; due to this reproductive habit, the fly population will drop significantly (Jordan, 1985). This technique was first used against the tsetse flies in Tanzania in the 1970s and effectively controlled the vector (Williamson et al., 1983). The researchers supported by the Tanzania Ministry of Agriculture and the United States Agency for International Development (USAID) set up a "fly factory" in Tanga Region (Broad, 1978; King and Crew, 2013). Thousands of unhatched male pupae sterilized with Cesium 137 were released to the wild every week, which led to an 81% reduction of the fly population in trial areas (Broad, 1978; Williamson et al., 1983; McCord, 2011). However, the lack of effective barriers resulted in the invasion of tsetse flies from uncontrolled places. More recently, from 1994 to 1997, after the release of nearly 8.5 million sterile male flies, the country successfully controlled *G. austeni* in the island of Zanzibar (FAO, 1998; Msangi et al., 2000). In 1997, the island was declared to be free from cyclically transmitted trypanosomiasis (Vreysen et al., 2000; McCord 2011, Malele, 2012). Zanzibar is an isolated island away from the mainland Tanzania, which provides natural barriers preventing tsetse reinvasion. In addition, only one species of tsetse fly existed on the island (Vreysen et al., 2000). These two conditions increased the probability of the success for tsetse control using sterile insect technique. However, for the mainland Tanzania, the effectiveness of sterile insect technique is challenged by tsetse reinvasions because of the lack of barriers. Also, the overlaps of the habitats for different species in mainland Tanzania require a more complicated "fly factory" with different species, which results in a higher cost. Enserink (2007) suggests that sterile insect technique only succeeds when the ratio of sterilized males to the wild males is higher than ten to one. Therefore, SIT is usually limited to areas with low tsetse population densities to begin with (Simpson 1958; Shaw et al., 2006).

2.3.3 Traps and Targets

Both traps and targets use blue and black panels of cloth as visual stimuli to attract tsetse flies to the control devices (Green, 1993; McCord, 2011). Blue is regarded as the most attractive color to tsetse, but black is more likely to promote a settling or entry response (Green, 1994). The targets are usually sprayed with insecticides to kill the tsetse fly, but for traps, the insecticides can be optional. Riverine species of tsetse fly (*Palpalis* group) can be effectively trapped by the devices using only the visual cues. However, savannah species (*Moristan* group) are more likely to be attracted by olfactory cues. Attractants like acetone, octenol, or cow urine are baited on the traps or targets to improve the efficacy of traps and targets (Belete et al., 2004). The traps are usually shaped in three dimensions while the targets are shaped in two dimensions (see Figure 2.3). Various designs of traps and targets have been created for controlling different species and even genders of the tsetse fly in various locations (Malele, 2012). The effectiveness of different types of tsetse traps (i.e. NGU, Epsilon and F3 types and Blue Biconical and Pyramidal traps) for the fly management in Mkwaja and Mivumoni ranches in the northeastern Tanzania was compared (Kasilagila, 2003).

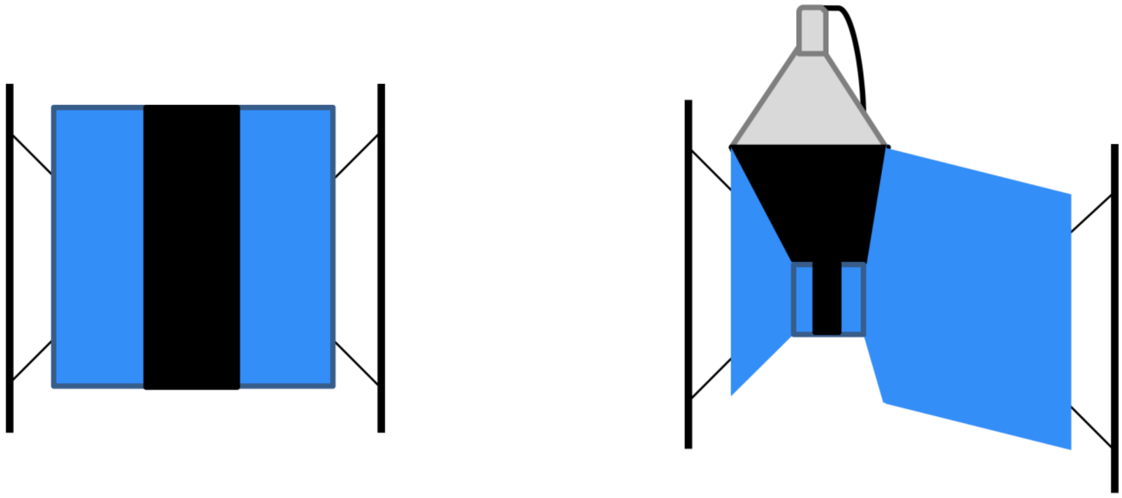


Figure 2.3: The tsetse target and the trap. *The target (on the left) is two-dimensional device and usually applied with insecticide; The NG2G trap (on the right) is three dimensional with insecticides as an optional choice (Adopted from McCord, 2011)*

These methods were usually applied to some small-scale and sporadic control programs in Tanzania. In 1990, tsetse trapping was employed for three months in the area of Mkwaja where cattle were first treated with Decatix for four months. The result of the integration of insecticide-treated cattle and traps for tsetse control showed that *G. pallidipes, G. m. morsitans* and *G. brevipalpis* were reduced by approximately 90, 100 and 70 percent respectively (Gao et al., 1990). Traps and targets were also used in control activities in northern Tanzania (Muangirwa *et al*., 1994c) and Kasulu (Daffa *et al.,* 2003); however, there are no detailed documents recording the effects (Malele, 2012).

2.3.4 Insecticide-Treated Cattle (ITC)

Insecticide-treated cattle is another common baiting technique. Cattle are usually treated with appropriate insecticide formulations, such as deltamethrin, alphacypermethrin, and cyfluthrin, by means of cattle dipping (Vale, Mutika, and Lovemore, 1999). The insecticides are poured, spotted or sprayed along the parts of the body where tsetse prefers to feed, especially the legs and belly (Torr, Hargrove, and Vale 2005; McCord, 2011). The treated cattle are often dispersed in tsetse-infested areas to kill tsetse flies and control the fly populations. This method succeeded in Kagera region to reduce the cases of animal trypanosomiasis from 19,300 to 2,383, and the deaths of animals from 730 to 29 in 1997 (Hargrove et al., 2000). On the four ranches of Kagera region, the prophylaxis of trypanosomiasis became unnecessary, since the tsetse flies had been almost eradicated (Hargrove et al., 2003).

However, insecticide-treated cattle is expensive and not always effective. Similar to the control activities in Kagera region, the insecticide-treated cattle with pyrethroids were also utilized in Mkwaja Ranch, Tanga region (Hargrove et al., 2000). To eliminate the tsetse population in the trial areas, about 8,000 cattle were dipped in synthetic pyrethroid deltamethrin (Decatix Cattle Dip and Spray formulation) with regular frequency and grazed over 250 km^2 lands in 1988 (Fox et al.,1993). The fly population decreased by over 90% within a year leading to a dramatic improvement in herd health (Fox et al., 1993). However, 11 reported cases of animal death caused by trypanosomiasis between 1990 and 1991 in the trial areas suggested that trypanosomiasis did not disappear completely (Hargrove et al., 2000). Additionally, although the high-levels of trypanosomiasis prophylaxis, deltamethrin dipping, and deployment of approximate 200 odor-baited targets were used in the study areas, the usage of Samorin and Bereni treatments after 1993 reflected that trypanosomasis and tsetse were still common (Hargrove et al., 2000). All told, the result of the control programs using insecticide-treated cattle on Mkwaja Ranch was not as effective as in Kagera Region.

The success of insecticide-treated cattle depends on several factors. First, different from targets and traps which can be deployed at specific densities, insecticide-treated cattle may not distribute over the control areas evenly due to the mobility of cattle (McCord, 2011). Cattle usually avoid the places frequented by tsetse flies allowing the endemic tsetse populations to remain. Second, the scale effects and rate of reinvasion also affect the outcomes of the control campaigns using treated cattle (Leak et al., 1995; Hargrove et al., 2000). In the Kagera case, the trial area (> $2000km^2$) regularly grazed with treated cattle covered a large proportion of the local fly belt. At the same time, the pyrethroids were also applied in the areas adjacent to the ranches, which effectively prevented tsetse reinvasion. However, on Mkwaja Ranch, the control area was only $250km^2$. There was no organized dipping in the areas adjacent to the ranch. Hence, the reinvasion of the tsetse flies from surrounding places contributed to the failed control effort. Third, the control activities in Kagera region took the advantage of the typical topography of trial area to avoid reinvasion problem (Hargrove et al., 2000). Karagwe Escarpment on the west side and heavy settlement on the east obstructed tsetse reinvasion in these directions. It became much easier to keep the trial areas free from tsetse after the control activities. Fourth, there may be some other unknown factors which can impact the effectiveness of insecticide-treated cattle, such as the ratio of cattle to wild animals (Hargrove et al., 2000). This ratio might influence the proportion of blood meals taken from treated cattle, which would affect the efficiency of this control method. Fifth, the ability and willingness of livestock keepers to purchase the insecticide might become an issue. It was calculated that each cow would roughly cost $0.20 (USD) annually on insecticide (Torr, Maudlin, and Vale 2007). This expenditure would be an obstacle in sub-Saharan Africa where 70 percent of populations live on less than $1.25 (USD) per day (World Bank, 2010; McCord, 2011).

2.3.5 Eradication (PATTEC)

Africa-wide tsetse eradication is the ultimate goal for all the tsetse control campaigns. However, the feasibility of eradication of tsetse flies has been critically reviewed by some researchers (e.g. Hargrove, 2003; Torr, Hargrove, and Vale, 2005), even completely contradicted by others, given the limited funding, environmental damages, and tsetse reinvasion problems (Rogers and Randolph, 2002). Still, some researchers are ambitious about tsetse eradication and believe that it is the best solution to change the current situation of African rural development constrained by tsetse and trypanosomiasis (Togo, July 2000; Kaboya, 2002; Kamuanga, 2003). In order to eradicate trypanosomiasis in Africa, the Pan-African Tsetse and Trypanosomiasis Eradication Campaign (PATTEC) will need to play a significant role in coordinating the continent-wide tsetse eradication, providing technical guidance, and obtaining funding (PATTEC, 2001; McCord, 2011).

PATTEC was established as a special Project under African Union-Department of Rural Economy and Agriculture (AU-DREA), with members such as Food and Agriculture Organization (FAO), World Health Organization (WHO), the African Union Inter-African Bureau for Animal Resources (AU-IBAR), and International Atomic Energy Agency (IAEA) (Taverne, 2001). PATTEC advocated sustainable approaches and claimed that the environmental impact of all control activities should be considered before the implementation (PATTEC, 2002). Besides, PATTEC also suggested the deployment of large-scale control campaigns and announced that eradication is a “once-and-for-all cost” (Kaboya, 2002; McCord, 2011). In July 2000, Tanzania joined the PATTEC, agreed on the coordinated control efforts, and agreed to use an Area-Wide and Sustainable Approach to eliminate tsetse and trypanosomiasis (Malele, 2012).

However, obstacles for PATTEC remain. First, the costs of tsetse eradication exceed the current economic ability of many African governments and institutions (Rogers and Randolph, 2002; McCord, 2011). Second, without any fallback position, the failure of Area-wide eradication is much more serious than that of control campaigns (Rogers and Randolph, 2002). Last but not least, cooperation among countries could result in an increase in foreign exchange debt (Rogers and Randolph, 2002). In consideration of all the challenges described, it becomes inevitable that the preference is for smaller-scale, less expensive, and more sustainable control methods.

2.4 Costing Tsetse Control and Cost Benefit

2.4.1 Costs of Tsetse Control Campaigns

The cost of field control using the previously described techniques has been recorded since the early campaigns. In 1910, the glutinous black clothes were regarded as a cost-effective method to control tsetse fly in the island of Principe (Madolado, 1910). Wilson (1953) indicated the cost of ground spraying with DDT was estimated at $47.5 (USD) per mile for eradicating *G. palpalis* in Kenya Colony. In 1991, NG2B tsetse trap created by

Brightwell et al. (1987) was baited with acetone and cow urine, for controlling *G.pallidipes* Austen and *G. longipennis* Corti in Kenya (Brightwell, Dransfield, and Kyorku, 1991). The cost of this improved trap was estimated to be about $8.5 (USD) per unit per annum (Brightwell, Dransfield, and Kyorku, 1991). For the aforementioned successful case of using sterile male technique in Zanzibar, Tanzania, approximate $6 million (USD) was spent during the study period (Fahey, 2013). More recently, about $12 million (USD) was spent on a "fly factory" for sterile male technique in Ethiopia, which was expected to eliminate tsetse flies in Southern Rift Valley by 2017 (King and Crew, 2013).

Besides the costs for control techniques in the field as described above, the costs for administration were also suggested to be included in the total cost for tsetse control campaigns (Barrett 1997, Shaw et al., 2007). In order to calculate the accurate costs for control activities, a detailed economic estimation for different alternatives to deal with tsetse and trypanosomiasis in Uganda was developed by Shaw et al. (2007) and included items used not only in field control operations, such as insecticide spraying, sterile male technique, as well as traps and targets, but also in some non-field activities, such as surveying, monitoring and administrative management (ADB, IAEA and PATTEC, 2004; Shaw et al., 2007).

2.4.2 Cost Benefit

Since the 1970s, there has been a noticeable reduction on the financial resources to support tsetse and trypanosomiasis control by African governments (Hargrove 2000). In addition, the control funding from donors has declined, with some donors concerned about the significant environmental impacts of extensive scale control campaigns. Others were suspicious of the benefits from the control activities, considering the limited success of the previous fly managements (Hargrove 2000). Therefore, it is of great necessity to weigh against the cost and benefit of the vector control (Shaw et al., 2007).

2.4.2.1 Cost Benefits for Animal Trypanosomiasis

Tsetse and trypanosomiasis depress African economic development (Scoones, 2014). Studies on the benefits and costs of tsetse control have been conducted extensively across Africa (for example, Itty, 1992; Swallow, 2000; IAEA, 2002; Alsan, 2014). Kristjanson et al. (1999) used an economic surplus model to analyze how demand and supply would be shifted, particularly in dairy and meat production on a continent-wide scale, with the assumption that a vaccine was developed for trypanosomiasis. Budd (1999) estimated how African agriculture would be improved with an increase in the number of cattle after the removal of tsetse flies in some large tsetse-infested areas in Africa. Some of the benefits of tsetse control were suggested including tripled milk production, doubled beef productions and a five-fold rise in the number of farmers who fertilize crops with manure (Kabayo, in IAEA press release, 2002). Return on investment of about 34% has been estimated after the eradication of tsetse flies in Ethiopia (Salifu, Asuming-Brempong, and Alhassan, 2010). Recently, the economic benefits of combatting bovine trypanosomiasis in Eastern Africa were mapped; this was achieved by weighing the benefits of each bovine (in $USD) and expanding the data to a square kilometer resolution, based on the distribution of cattle (Shaw et al. 2014). The results showed a maximum benefit for stakeholders at nearly $2.5 billion (USD) and an average of approximately $3,300 (USD) per square kilometer of tsetse-infested area.

2.4.2.2 Cost Benefits for human Trypanosomiasis

For controlling the human trypanosomiasis, the benefits should include the costs for both human case finding and treatment (Shaw, 1989). Shaw's study created a standardized economic measure for the benefit called a benefit unit, which was defined as a year's infection avoided because of tsetse and trypanosomiasis control for each vulnerable person (Shaw, 1989). For some cases, in which the disease influences the routine work of the patient, the loss of individual income should also be included in calculating the benefits.

Besides, in Shaw's (2003) study, the relationship between human population density and the cost-benefit balance during the tsetse control project was analyzed, as shown in Figure 2.3. The red line represents the relationship between the human population density and the total discounted benefits of tsetse control. In the aforementioned study, a 10 percent discount rate was applied to convert the costs and benefits to present values (Itty et al., 1995). The number of people who benefit from control activities is low at low population densities, despite high tsetse populations. As people start colonizing the control areas, increases in the number of livestock improve not only meat and dairy production but also crop production due to animal traction (Shaw, 2003). However, after the human population exceeds some threshold, a large number of livestock may not be able to be kept, which leads to a reduction of benefits (Shaw, 2003). As shown in the theoretical line chart, the control benefit increases immediately and rapidly at low population density, however, higher population density has a lower and later control benefit. The blue line indicates the relationship between the total discounted costs and human population density. As population densities rise, the habitats of tsetse flies are occupied by humans; thus, the costs to control the tsetse-infested areas declines. The inversely proportional relationship might be caused by the discounts as previously described. There are two turning points in the economics of long-term tsetse control operations: the first one occurs when the human population densities and the associated livestock population densities increase to a certain size which makes the control benefits equivalent to the control costs; The later one occurs when the rising human population densities affect the livestock population and livestock numbers have ceased to expand as they have reached carrying capacity, so that the benefits on agricultural productions would be only enough to cover control costs (Shaw, 2003).

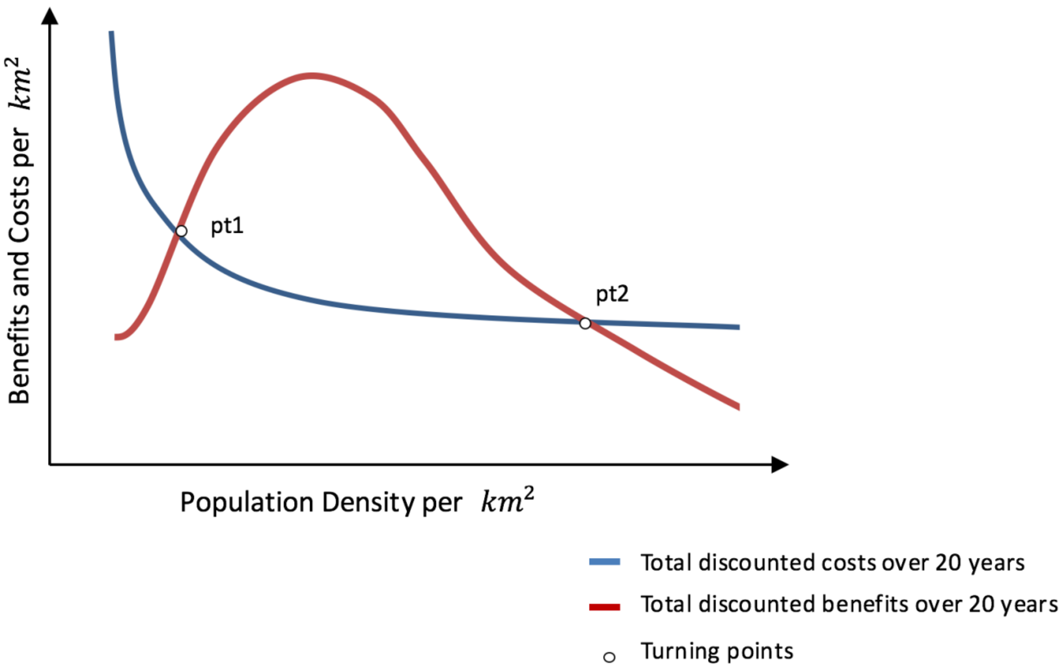


Figure 2.4: Theoretical model. *The figure shows the relationship between cost-benefit balance and population density during tsetse control campaigns (Adopted from Shaw, 1986)*

CHAPTER 3

METHODOLOGY

The identification of tsetse infested areas is of primary importance. The Tsetse Ecological Distribution (TED) model (DeVisser et al., 2010) which incorporates both a fundamental niche model and a species movement model was used to produce the predicted dynamic distributions of the tsetse flies. Model parameterizations and processes will be described in section 3.1 below. These tsetse distributions were then used for both the control cost analysis and cost-benefit analysis.

Section 3.2 describes a cost model adopted from McCord et al. (2012) to calculate the expenses for tsetse management in Tanzania. Given the seasonal fluctuations of the tsetse distributions, control reservoirs (CRs) were identified as the places to conduct tsetse control campaigns (McCord et al., 2012). Tsetse zones (TZs) defined as the maximum spatial extent of tsetse distributions over the study period were also identified (McCord et al., 2012). The identification of CRs and TZs will be detailed in 3.2.1 as below. Fly management tasks were divided into field-control and non-field control. The cost model (McCord et al., 2012) designed to at maximize limited resources for tsetse control was applied to both the control reservoirs and tsetse zones and is discussed in 3.2.2.

Given the limited funding for tsetse control, it is necessary to identify the most beneficial areas to conduct the tsetse control campaigns. The cost benefit analysis for tsetse control activities will be described in section 3.3. Beneficial control areas are the highly populated locations with high tsetse burdens. The details of each component in the cost-benefit balance model for tsetse control shown in Figure 3.1 will be elucidated in this chapter.

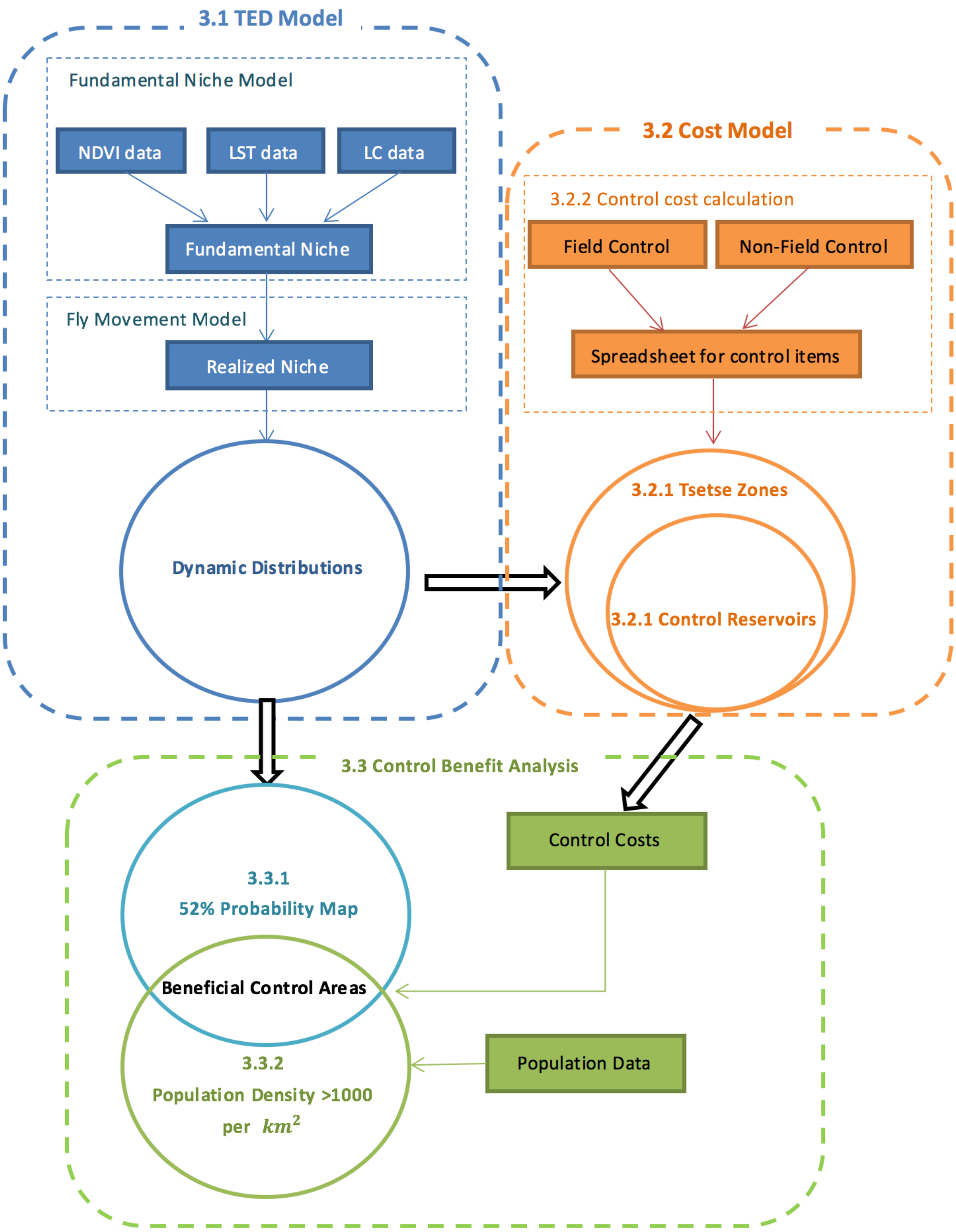


Figure 3.1: Data Frame Diagram. *Cost-benefit balance model for tsetse control*

3.1 Tsetse Ecological Distribution (TED) Model

Given the spatio-temporal fluctuations of tsetse distributions, remotely sensed data are often applied to simulate the ecological niche of the tsetse flies (Rogers et al., 2004). The

Tsetse Ecological Distribution (TED) model, developed by DeVisser et al. (2009) offers a solution for identifying tsetse fly habitats. This model is designed to predict the spatial and temporal distributions of the *Morsitans* group (Savannah) (DeVisser et al., 2010). This group is the most widely distributed in Tanzania. The TED model consists of two sub-models: a fundamental niche model and a fly movement model (DeVisser et al., 2010). The suitable habitats for tsetse flies are identified using a fundamental niche model based on suitable land cover with woody vegetation (Pollock, 1982a; Pollock, 1982b), moisture (NDVI>0.39) (Lovemore, Flint, and Cockbill, 1988; Williams et al, 1992b) and temperature (day temperature: 17℃~40℃; night temperature: 10℃~40℃) (Mellanby, 1936; Leak, 1999; Muzari and Hargrove, 2005). The fly movement model calculates the realized niche based on the fundamental niche model by expanding the fly distributions at a rate of 500 m (2 grid cells) per 16 days (Leak, 1999; Hargrove, 2000). If the fly distributions expand to pixels which are not the suitable habitats, the TED model predicts no tsetse exists in these locations. Similarly, this rule also applies to pixels changing from suitable to unsuitable habitats where the existence of tsetse distributions was previously simulated (DeVisser et al., 2010). Thus, the tsetse distributions will shrink when the surface areas of suitable tsetse habitat decline. In this way, the TED model produces a unique tsetse fly distribution with a 16-day MODIS interval, thus, track tsetse distributions spatially and temporally.

The data inputs for the TED model were MODIS Normalized Difference Vegetation Index (NDVI) data, land surface temperature (LST) data, and land cover data for Tanzania. The MODIS Terra NDVI 250m V005 (MOD13Q1) product from NASA was used as a surrogate for available moisture. Here we used 253 MODIS NDVI scenes acquired from 1 January 2001 to 19 December 2013, with an increment unit of 16 days. Upon inspection of the MODIS NDVI data, a scan line error was identified for the image taken on the 305th day of 2004; a value for the missing data was interpolated using the mean data values for the same location on 289th and 321st day of 2004. MODIS Terra Day and Night LST 8-day L3 Global 1km (MOD11A2) V005 products were acquired from NASA to serve as the daily temperature reference. 16-day interval LST data were used in the fundamental niche model to match the same scene of NDVI data. MODIS Terra+Aqua Land Cover Type 1 Yearly L3 Global 500m V005 (MCD12Q1) products from NASA with 1km spatial resolution were employed to identify the vegetation covered land for tsetse habitats.

The TED Model required a starting tsetse distribution for initialization. However, due to the potential overestimation of the first initialization and the unknown tsetse starting distribution, data for two years, 2001 and 2002, were used. The output of the model initialization served as an input for the starting distribution, ensuring a stable tsetse distribution. Fly fundamental niches were expanded using the movement rate from the fly movement model, producing the realized niche, which resulted in 253 realized niche distribution maps containing binary data regarding the presence or absence of tsetse flies. These distribution maps were then summed (i.e. $\sum 253\ binary\ distribution\ maps$) and divided by 253 to create the probability distribution map of tsetse flies. Each pixel value represented the percentage of tsetse presence during the study period.

3.2 Cost Model

Decision-making and economic strategies for tsetse control are complex, with a wide range of choices to be made on control location, timing and methods (Shaw et al., 2013). This section focuses on each of these points and uses a spreadsheet cost model to calculate the cost of fly management in Tanzania.

3.2.1 Definition of Fly Belt, Tsetse Zones, and Control Reservoirs

The TED outputs of binary tsetse distribution maps over the study period are used in this sub-section aimed at detecting the exact location and timing of constrained tsetse distributions optimal for tsetse management campaign. These constrained distributions which are the suitable habitats limited by seasonal variations are named as control reservoirs (CRs) (McCord et al., 2012). Also, another feature, tsetse zones (TZs), is also introduced to compare to the CRs. TZs are defined as the maximum spatial extent of tsetse distributions over the study period (McCord et al., 2012). The aforementioned three layers for tsetse control are shown in Figure 3.2.

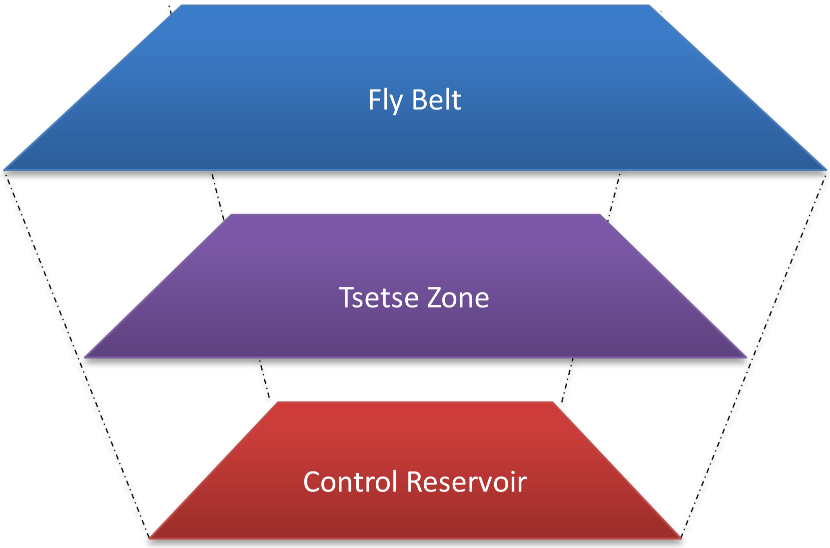


Figure 3.2: The three layers for tsetse control. *Layers for fly belt, tsetse zone, and control reservoir.*

3.2.1.1 Fly Belt

Tsetse fly belts are usually created to separate the control areas for effective fly management and serve as the administrative units during tsetse control activities (McCord et al., 2012). However, there is no uniquely accepted definition of fly belts; thus, no exact boundaries of fly belts exist (McCord et al., 2012). Historically and currently, the fly belts have been generated based on the distribution of fly species and influenced by different climate conditions and land covers (Ford and Katondo, 1975; Rogers and Robinson, 2004; Rollinson and Hay, 2012). According to Ford (1971), the fly distributions of Glossina Morsitans group could be simply separated into three fly belts, one in coastal areas of Tanzania, one in western areas and one in eastern Lake Victoria regions. Each belt comprised different species: *G. morsitans* were located in both coastal and western areas; *G. pallidipes* were distributed in the same areas as *G. morsitans* and also in western Lake Victoria areas; *G. swynnertoni* occupied only eastern Lake Victoria areas. With similar tsetse distributions generated by TED model, three fly belts were also suggested in this study, i.e. Coastal and Southern Tanzania Region Belt, Western Tanzania & Great Lakes Region Belt, and Eastern Lake Victoria Region Belt. The creation of fly belts helped the identification of CRs and TZs in the following sections.

3.2.1.2 Tsetse Zones

Tsetse zones (i.e. the maximum spatial extent of distributions) nested in each belt were identified following methods outlined by McCord et al. (2012). Two hundred fifty-three fly distribution maps were summed to produce the maximum extent map. The fly distributions in the maximum extent map were expanded by 3 km, considering these two conditions: 1) a fly can move with a front distance of 1km per month; 2) the main rainy season (or the "long rains") lasts 3 months from March to May in Tanzania, (Leak, 1999; Hargrove, 2000; McCord et al., 2012). If the tsetse distributions were separated from the major distributions with an area over 150 km^2 after expansion, they were regarded as isolated TZs; otherwise, smaller isolated TZs (< 150 km^2) were grouped to the nearest isolated TZ meeting the size requirement (i.e. >150 km^2) (McCord et al., 2012). The procedures to identify the TZs are given in Figure 3.3

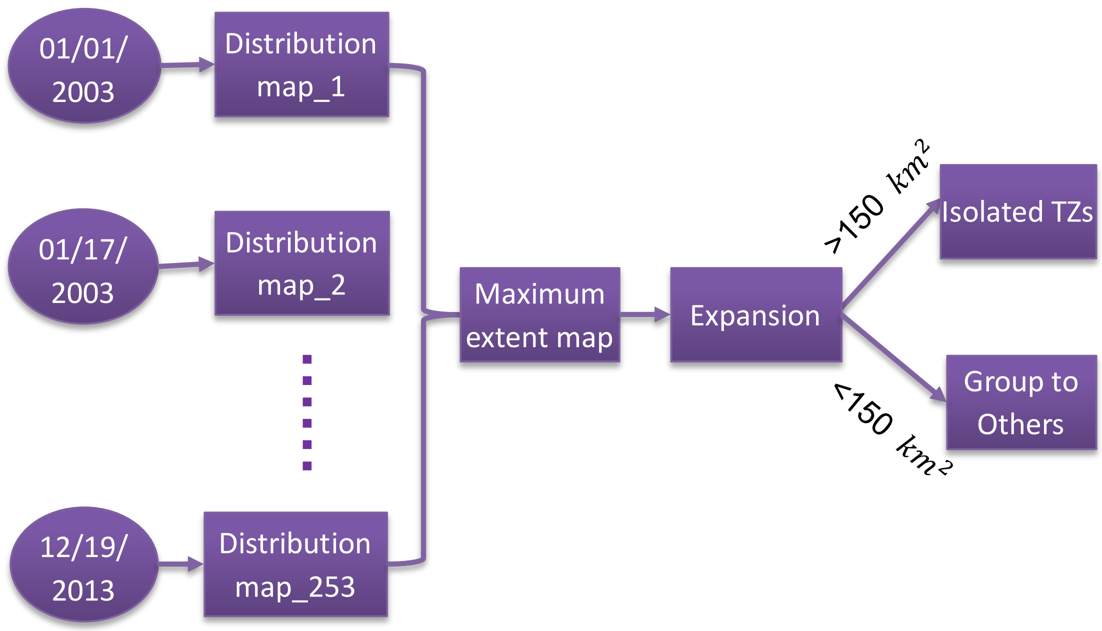


Figure 3.3: Procedures of TZ identification

3.2.1.3 Control Reservoirs

In contrast to TZs, CRs are the suitable habitats temporally constrained by seasonal climatic conditions (McCord et al., 2012). According to the dynamic tsetse control model Tsetse Muse, a 216-day control period using targets can eradicate tsetse by reducing the fly population to 0.5 flies per km^2 (Vale and Torr, 2005). Therefore, a targeting period of 216 days is identified based on the minimum area interval of the tsetse distributions in a year (McCord et al., 2012). Although the length of the targeting period is fixed, the starting date of the targeting period for each TZs/CRs might be different, which will be described in the next chapter. This targeting period is optimal for eliminating tsetse since it generally covers the cool dry season and the short rain season; traps and targets can perform more effectively without the impact of rains on insecticide (Williams et al., 1992a). It is also more convenient to set up, replace and repair targets in dry seasons.

The procedure of CR creation in this study was to initially detect the presence or absence of tsetse flies within each TZ for eleven years using the TED model. In order to ensure that CRs cover fly distributions over the 216 targeting days, tsetse presence or absence in this period with the largest surface areas for each year was selected and summed to generate a probability map. The reason for choosing the largest surface areas was to ensure the CRs covered the tsetse distributions for the whole 216 targeting period. Finally, locations with a probability value over 50% were selected as CRs (DeVisser et al., 2010; McCord et al., 2012). The threshold of 50% was chosen because CRs represent the places where tsetse is reliably present, rather than the sites where the presence of tsetse fly is associated with abnormal climatic events. The flow chart to identify CRs shows in Figure 3.4.

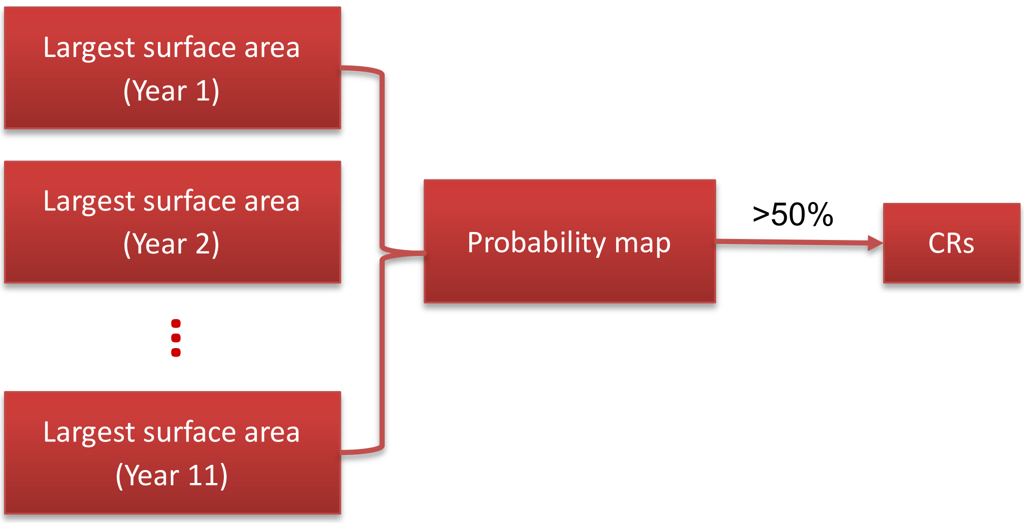


Figure 3.4: Procedures of CR identification

3.2.2 Tsetse Fly Management

The data and methods used for cost analysis on tsetse control in Tanzania were developed according to three previous studies. The input data to calculate non-field control cost were based on AU, IAEA, and ADB (2004) document. For the analysis of field control, we adopted Shaw et al.'s (2007) input data and flows of field control operations. The above two studies were then combined to analyze tsetse control cost in Tanzania, following McCord et al.'s (2012) method used in Kenya. A list of the selected inputs and their prices to accomplish the tsetse control campaigns used in this study is given in Table 3.1. These costs are calculated at end 2010 prices.

Table 3.1: *Costs of selected inputs used in all tasks in tsetse control campaign*

Inputs	**Input life (yrs)**	**Total Cost (aunual cost)**
General equipment		
4*4 vehicle	5	$30,000 ($6,000)
Lorry	5	$30,000 ($6,000)
Bicycle	6	$80 ($13.33)
Motorbike	6	$2,500 ($416.67)
Laptop computer	3	$3,000 ($1,000)
Radio set	5	$500 ($100)
Camping equipment	5	$400 ($80)
Specialized equipment		
Target	1	$8 ($8)
Trap	1	$8 ($8)
Satellite imagery	6	$700 ($116.67)
Land use/veg. map	6	$20,000 ($3333.33)
GPS unit	3	$30 ($10)
Dissection microscope	6	$1,000 ($165.67)
Compound microscope	6	$2,000 ($333.33)
Portable Generators	5	$1,000 ($200)
Printer	5	$500 ($100)
Dissection kit	6	$110 ($18.33)
Sample Vial	1	$0.1 ($0.1)
Consum.Parasit.	6	$5,000 ($1,000)
Sampling equipment	5	$1100 ($220)
Recurring specialized equipment		
Training - field staff	1	$125 ($125)
Delta-methrin	1	$350 ($350)
Octenol	1	$1.50 ($1.50)
Acetone	1	$3.50 ($3.50)
Fuel/maint. vehicle	1	$32/day
Human resouce salaries		
Team leader	1	Varies
Entomological ass't	1	$25/day
Laborer	1	$5/day
Driver	1	$17/day

Adopted from McCord et al. (2012)

Notes: The salaries of "Team Leader" varies depending on different control activities, since the responsibilities vary across activities. The types of team leaders include general team *leaders ($30/day), biochemists ($30/day), consultants/ecologists ($130/day), medical officers ($30/day), socio-economists ($130/day), and veterinary officers ($30/day).*

3.2.2.1 Non-field Control

Non-field control includes surveying and monitoring tasks, such as socioeconomic survey, and sleeping sickness survey as well as environmental and entomological monitoring. It also includes administrative costs, since all activities in the field are managed and supervised by a central administration office (Shaw et al., 2007). Non-field control activities are usually performed before field control. These studies and surveys help to conduct and support tsetse control in the field.

1) Entomological Survey and Tsetse Fly Population Genetics Survey

This task including the trapping and getting samples of tsetse flies, as well as studying the genetics of the sampled tsetse flies occurs in Year 1(McCord, 2011). These surveys take 180 days as a total.

2) Socioeconomic Survey

The socioeconomic survey is an important task to study the socioeconomic status of the households living in the tsetse-infested areas before the implement of field control (McCord, 2011). The results of the survey directly influence the evaluation of the control benefits after the removal of tsetse flies. This task takes place in Year 1 and usually lasts for sixty days.

3) Sleeping Sickness Survey

The sleeping sickness survey is usually conducted in the second year to study the risk of getting the infection of sleeping sickness. The duration for this survey is also sixty days.

4) Parasitological and Serological Data Collection

This task includes parasitological and serological tests to study the prevalence of animal trypanosomiasis (Seck et al., 2010). The parasitological and serological data collection occurs in Year 2 for 180 days to collect the information for animal trypanosomiasis, aiming at identifying where to target to prevent AAT. This task occurs for 180 days after the field control operations to test if the disease has been controlled in the area.

5) Environmental Impact Assessment

The environmental impact assessment includes identifying if the food sources or harvesting practices will increase chances for human exposure to deltamethrin, finding measures to avoid or reduce any impacts to humans and environments, as well as studying the biodiversity of non-target organisms such as soils, insects, and aquatic organisms (MoLD, 2013). The operation will last for ninety days in Year 2.

6) Sleeping Sickness Active Case Finding

This survey is undertaken for the surveillance of the areas where sleeping sickness is known to be endemic, and the treatment of diagnosed cases (McCord, 2011). This task occurs each of the years that field control occurs (i.e. Year 3, Year 4, Year 5). The duration is ninety days.

7) Environmental and Entomological Monitoring

In this operation, the environmental and entomological parameters are under surveillance to estimate the impact due to the field control (McCord et al., 2012). The monitoring occurs each of the years that field control operations are taking place (i.e. Year 3, Year 4, Year 5). The duration is ninety days.

8) Administration and Office Support

Administration and office support is a central coordinating office to organize meetings, and conduct or supervise all the surveys, monitoring and control operations in the field. It usually runs throughout the whole fly management, that is, six years in this study.

3.2.2.2 Field control

Field control operations comprise two phases: deployment phase and targeting phase (McCord, 2012). The deployment phase usually takes place in four months before tsetse flies maximized their spatial footprint. During this period, targets are deployed, baited and sprayed with deltamethrin insecticide (McCord, 2011). Once the tsetse flies are confined to the spatial limits of CRs, the targeting phase is performed for the next seven months (McCord et al., 2012). During this period, the targets are left to eliminate tsetse flies. Since some targets might be damaged or stolen, they should be re-baited with octenol and acetone, re-sprayed and replaced from the third month of the targeting period to the sixth month (Brightwell et al., 2011; McCord, 2011). McCord et al. (2012) suggest that 17 percent of targets be replaced during this period to re-treat the targets with insecticides (McCord et al., 2012). During these two phases, it is assumed that a laborer is able to set up, bait and spray four targets a day (McCord et al., 2012). Schedules for each task in both non-field control and field control are tabulated in Table 3.2. The detailed items used in non-field control activities and the determination of the number of capital and labor inputs are listed in Table 3.3. The items used in the field and the determination of the number of field control capital and labor inputs are listed in Table 3.4.

Table 3.2: *Schedule of tasks in tsetse control campaign including field and non-field control*

Year (Discount Factor)	Activity	Duration (days)
1	ET	180
-1.21	SE	60
2	SS	60
-1.1	PS	180
	EA	90
3	Coastal & Central Tanzania Belt Field Control	336
-1	CF	90
	EE	90
4	Western & Great Lake Region Belt Field Control	336
-0.909	CF	90
	EE	90
5	Eastern Lake Victoria Region Belt Field Control	336
-0.826	CF	90
	EE	90
6	PS	180
-0.751		

Source: Adapted from McCord et al. (2012).

Notes: Field control includes 120-day development and 216-day targeting phase.

Non-field control: ***ET*** *– Entomological Survey and Tsetse Fly Population Genetics Survey.* ***SE*** *– Socioeconomic Survey.* ***SS*** *– Sleeping Sickness Survey.* ***PS*** *– Parasitological and Serological Data Collection.* ***EA*** *– Environmental Impact Assessment.* ***CF*** *– Sleeping Sickness Active Case Finding.* ***EE*** *– Environmental and Entomological Monitoring.*

Table 3.3: *Determination of the number of non-field control capital and labor inputs*

Input	Explanation
Entomological Survey	
Teams	One team consisting of a team leader, three entomological assistants (EAs), and one driver assigned for each 2,000 km^2 surveyed.
Equipment	**One per team:** Dissection microscopes, Compound microscopes, Portable generators, Camping equipment, Printer, Laptops, Radio sets; **Two per team:** GPS Units, Motorbikes, Dissecting kits; **Traps:** one per 10 km^2.
Tsetse Fly Population Genetics Survey	
Teams	One team consisting of a team leader, three EAs, one biochemist, two lab techs., and one driver assigned for each 10,000 km^2 surveyed.
Equipment	**One per team:** Satellite Imagery, 4*4 Vehicle; **Land Use/veg Map:** one for all teams.
Socioeconomic Survey	
Teams	One team consisting of a team leader assigned for each 2,000 km^2 surveyed, and one socio-economist, two data clerks assigned for each 10,000 km^2 surveyed, and one enumerator to conduct household survey for each 125 km^2.
Equipment	**One per team:** 4*4 Vehicle; **Four per team:** Motorbike; **Bicycles:** one per enumerator.
Sleeping Sickness Survey	
Teams	One team consisting of four medical officers and a driver for each 10,000 km^2 surveyed.
Equipment	**One per team:** laptops, 4*4 Vehicle; **Four per team:** GPS Units.

Table 3.3 (cont'd)

Parasitological and Serological Data Collection	
Teams	One team consisting of a team leader, two lab techs., one lab assistant, one veterinary, and one driver assigned for each 2,500 km^2 surveyed.
Equipment	**One per team:** 4*4 Vehicle, PCV Reader, Haematocrit Centrifuge; **Four per team:** Motorbike, Cool Boxes; **One per four teams:** Consumables parasitology, Comsumables serology, ELISA Reader, Computer ELISA Work, Trypanocidal Drugs (one year).
Environmental Impact Assessment	
Teams	One team consisting of one ecologist, two assistants, and two drivers for each 5,000 km^2 surveyed.
Equipment	**One per team:** 4*4 Vehicle, Radio sets, GPS Units; **Two per team:** Compass, Measuring Tape, Binoculars. **One for two teams:** Sampling Equipment, GIS Processing
Sleeping Sickness Active Case Finding	
Teams	Three teams consisting of four medical and one driver for each team assigned to areas where sleeping sickness has been reported.
Equipment	**One per team:** 4*4 Vehicle, Drugs (Mel-B, Suramin, Pentamidine); **Two per team:** Laptops; **Four per team:** Dissection Microscopes, Hematocrit Centrifuges, Portable Generators, Bench Centrifuge, GPS Sets, Pipettes; **Bicycles** (thirty per team), **Laboratory reagents** (one for all teams), **Safari Day Allowances** (eight per team).
Entomological Monitoring	
Teams	One team consisting of a team leader, two EAs, and one driver assigned for each 2,000 km^2 monitored.

Table 3.3 *(cont'd)*

Equipment	**One per team:** 4*4 Vehicles, Dissection microscopes, Compound microscopes, Portable generators, Camping equipment, Printer, Laptops, Radio sets; **Two per team:** Motorbikes, Dissecting kits.
Environmental Monitoring	
Teams	One team consisting of one consultant, two assistants, and one driver assigned for each 5,000 km^2 monitored.
Equipment	**One per team:** 4*4 Vehicles, GPS Units, Compass, Measuring Tape, Binoculars, Radio sets; **One per two teams:** Satellite Imagery, GIS Processing, Sampling Equipment and Materials; **Traps, Sample Vials:** One for 10 km^2.

Source: Adapted from McCord (2011).

Table 3.4: Determination of the number of field control capital and labor inputs

Input	Explanation
Targets	Initially, four targets deployed per km^2. Then, during the sixth month of the control period, an additional 17 percent of those initially deployed are placed in the field to replace damaged targets.
Teams	One team consisting of one team leader, eight laborers, two EAs, and one driver for every 3,840 targets initially deployed. 3,840 is the number of targets that can be set up in four months under the assumption that one laborer deploys four targets per day.
GPS Units	Two GPS units per team.
4*4 Vehicles	One 4*4 vehicle per team.
Lorries	One lorry to carry equipment per team.
Camping Equipment	Eight sets of camping equipment (i.e., one set per laborer) per team.
Stationary	One set of stationary per team.
Batteries	Two sets of batteries (for GPS units) per team.
Training Course for Field Staff	Each EA should take the course.
Deltamethrin	One liter of deltamethrin insecticide per 112 targets. This is found by assuming that 1 L of deltamethrin, when diluted to a 0.3 percent active ingredient final solution, provides 67 L of mix. Each target receives two applications of the mix at 300 ml per treatment.
Acetone	100 ml applied to each target on three occasions during control.
Octenol	One sachet of octenol applied to each target on three occasions during control.

Source: Adapted from McCord (2011).

3.2.3 Cost Calculation

The costs for controlling the tsetse fly depend on the items used in different control operations. Field and non-field control costs for each item were converted to the lifetime annual costs (see the examples in Table 3.1). Following Shaw et al.'s (2007) economic guideline, the annual price of each item used in tsetse and trypanosomiasis control should be discounted to its present value. Discounts of each year's price depend on which year is the baseline. According to the analysis of Shaw et al. (2007) and McCord et al. (2012), the year field control started is regarded as the baseline, which is Year 3 in this study. Compound interest should be added to the item price before the baseline year, while for the years after, they should be subtracted from the price. In this study, as typically used in livestock projects, a 10 percent discount rate was applied (Itty et al., 1995; Shaw 2003; McCord et al., 2012). Discount factors for each year were then calculated based on the discount rate through the equation below (McCord et al., 2012):

$$DiscountFactor = (1 + r)^t \qquad \text{Equation 1}$$

where r is the discount rate which equals to 10 percent; t is the year when the discount factor is being calculated (i.e. $t_{Year1} = 2$, $t_{Year2} = 1$, $t_{Year3} = 0$, … $t_{Year6} = -3$).

In order to save resources and conserve the control budget, capital items are shared in different operations when possible. During the first two years of the fly management, the capital items for administration, surveying, and monitoring are shared with other similar activities. Due to the long duration of field control, the field control inputs in a belt cannot be shared with any non-field activities. However, the field control capital items in one belt can be shared with field control other belts, since field control operations in different belts are performed in separate years. Once an item is shared by separate activities in a year, its annual cost is divided evenly for each activity. Finally, after accounting for shared resources, the total costs in each year for field and non-field control are summed by adding the annual prices of all the items.

3.3 Cost Benefit Analysis

People most likely to be exposed to the tsetse fly usually work in agriculture and animal husbandry (WHO, 2016). Given the importance of human behavior in the manifestation of the disease, the effective new approaches to control the trypanosomiasis should gather the information about human populations and their activities in rural and peri-urban areas (Fournet et al., 2000). Therefore, the spatial distribution of population in Tanzania needs to be considered to balance the cost-benefit equation. The control campaigns in tsetse habitats with a large population can maximize the control benefits through the maximum reduction of potential exposures. We define the beneficial control areas (BCAs) as the highly populated areas with frequent presence of the tsetse flies.

3.3.1 52 Percent Probability Map

Given the definition of the BCAs, the frequency of tsetse presence is a significant factor affecting the final decision-making. Therefore, it is important to find out the threshold to identify the tsetse-frequented areas. DeVisser et al. (2010) used the TED model to predict dynamic tsetse distributions from 2001 to 2009 in Kenya. They defined the locations with tsetse presence from 50% to 90% as tsetse reservoirs and the locations with above 90% tsetse presence as tsetse refugia. During his procedure to identify the tsetse reservoirs and refugia, the scenes that predicted the minimum tsetse surface area for each year were combined and converted to a tsetse presence percent probability map. The identification of tsetse reservoirs and refugia were based on this probability map. McCord et al. (2012) also used a 50 percent threshold to identify the CRs to analyze tsetse control costs in Kenya. This threshold was chosen based on the probability map which was produced by summarizing tsetse distribution map with maximum tsetse surface area during the cool dry season for each year. They thought it was necessary to target the place where tsetse was reliably present in tsetse control campaigns. The 50% break point in their study helped to exclude the sites where tsetse fly was present only because of the abnormal climate conditions.

In this study, to determine the threshold for the tsetse-frequented area for BCAs, the tsetse presence probability map generated by the TED model as described before was used as the fly distributions. It is important to note that the probability map created here covers the whole study period from 2003 to 2013, because the risk of getting the infections of trypanosomiasis needs to consider the long-term effects of tsetse presence, rather than the seasonal effects. Initially, the histogram of the probability map with 253 (i.e. the number of scenes) breaks was plotted (Figure 3.5). As shown in Figure 3.5, the number of pixels decreases dramatically from approximately 90,000 at 0.04% tsetse presence to 25,000 at 23 percent tsetse presence. The pixel numbers generally fluctuate in a low-value range between 25,000 and 27,000 until the noticeable turn point shown at around 50% of tsetse presence. An apparent surge in pixel numbers is observed after the tsetse presence reaches 50%. The pixel numbers increase to the peak of 86,000 when the tsetse presence increases to around 96%, after which the pixel numbers drop sharply. The tendency of the histogram shows that most areas in Tanzania have a tsetse presence below 23% or between 50% and 96%. Secondly, to delineate the trend of tsetse presence frequencies, different numbers of bins (i.e. 20, 10, and 4) were used to break the histogram down in Figure 3.6 (a), (b) and (c), respectively. Ten bin and four bin values show a flat valley in the tsetse presence between 20% and 50%. Four bin values simply and clearly delineate the trend of tsetse presence, which indicates that four classes can be reasonable to classify the probability map. Finally, to pinpoint the threshold, the natural breaks classification was applied to classify the tsetse presence probability map into four classes in Arc Map 10.2 (see Figure 3.7). 23%, 52%, and 77% were identified as the break points. 52% was eventually selected as the exact threshold, and areas with over 52% tsetse presence were defined as tsetse-frequented areas for the BCAs.

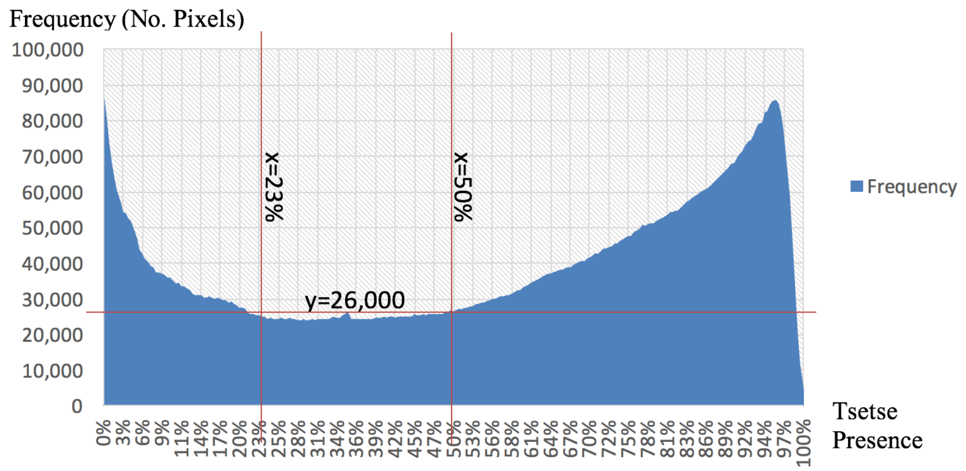
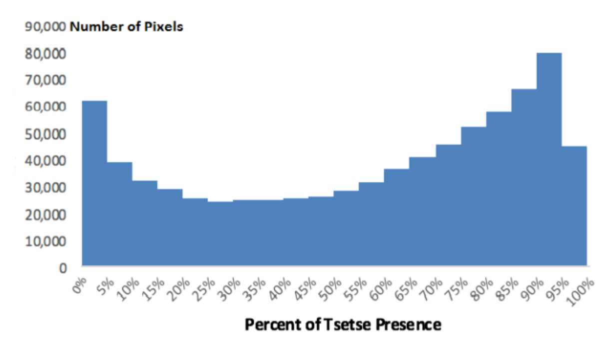
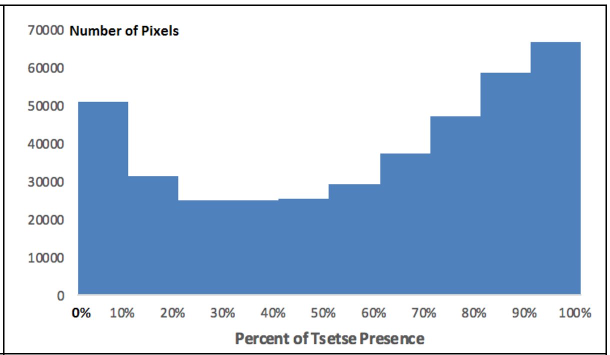


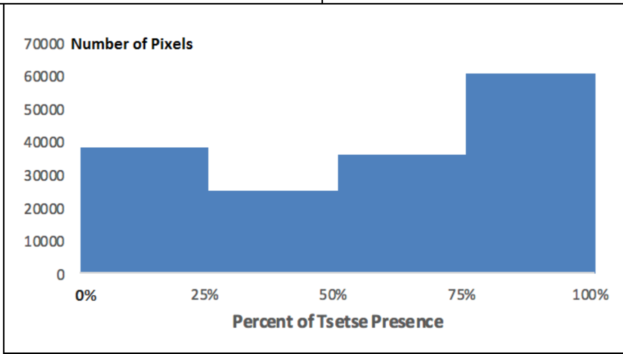
Figure 3.5: Histogram of tsetse presence



(a) 20 bins



(b) 10 bins



(c) 4 bins

Figure 3.6: Histogram of tsetse presence with different breaks. *Figure (a) shows the histogram of tsetse presence broken down in 20 bins; Figure (b) shows the histogram of tsetse presence broken down in 10 bins; Figure (c) shows the histogram of tsetse presence broken down in 4 bins*

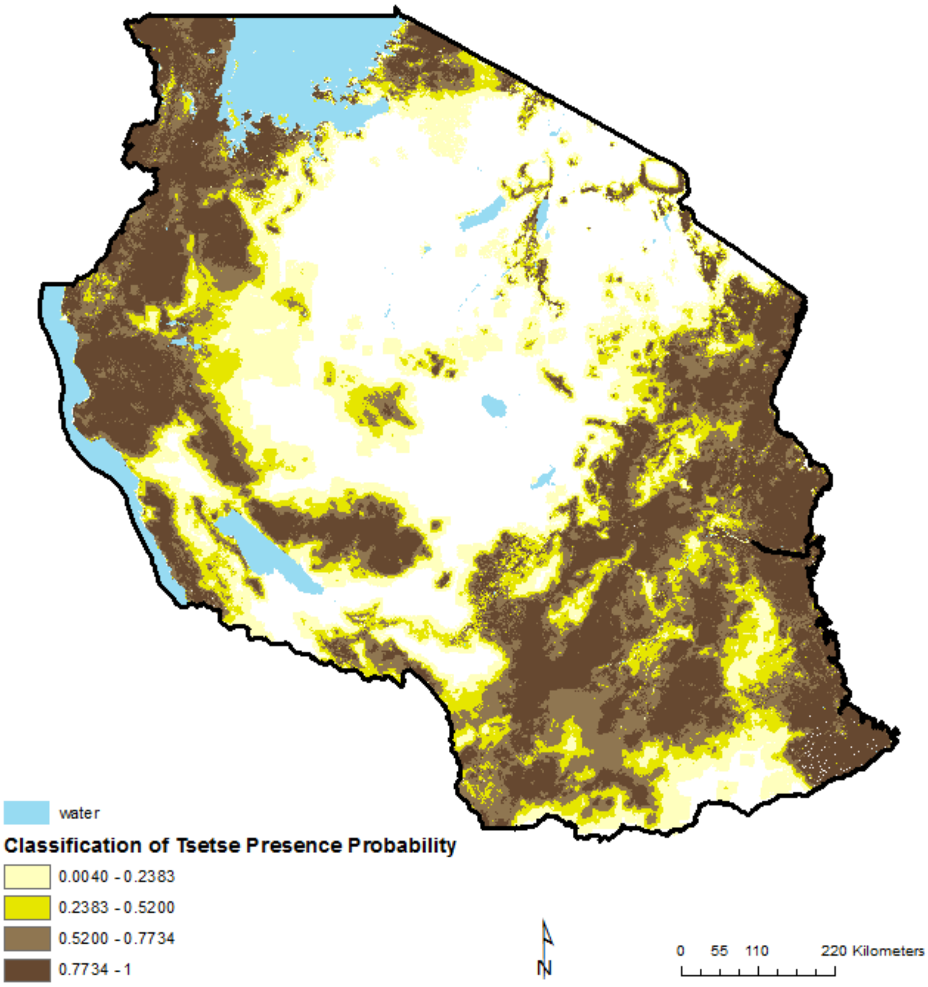


Figure 3.7: Classification of tsetse presence probability map with natural breaks. *Areas shown in brown are defined as tsetse-frequented areas)*

From the perspective of exposure potential, the infection of trypanosomiasis caused by the bite of the infected fly occurs randomly and is influenced by many factors, such as the frequency of tsetse presence, the fly population, and the biting preference of different tsetse species. Areas with the relatively higher probability of tsetse presence indicate that the tsetse fly is more likely to be present in those places, partly resulting in a higher potential risk of human-fly contacts. Areas with tsetse presence above 52% suggest a reliable existence and even a high frequency of the tsetse fly during the study period. The chance for humans to get the infection would be higher within these areas. The classified tsetse-frequented areas (i.e. locations with over 52 percent tsetse presence) account for 59.5% of the areas where the fly appear at least once from 2003 to 2013. The Ministry of Livestock and Fisheries Development (MLFD) reported that the overall tsetse infested risk areas occupied about 42.5 % lands of Tanzania in 2011(MLFD, 2011). This number is close to the proportion of the surface areas produced by 52 percent tsetse probability map (i.e. 39.6%). However, the procedures and data to identify this 42.5% tsetse infested risk areas were not documented. Since the presence of tsetse fly primarily depends on the types of land cover, without any information about the land cover MLFD used, the 42.5% tsetse infested risk areas might not serve as a strong support here. The comparison about the selection of different thresholds on tsetse presence in three different studies (i.e. aforementioned studies by DeVisser et al. (2010) and McCord et al. (2012), and this study) were summarized in Table 3.5.

Table 3.5: *Comparison of different thresholds on tsetse presence in three different studies*

	DeVisser et al. (2010)	McCord et al. (2012)	This study
Definition (threshold)	tsetse reservoir (50-90%) tsetse refugia (90%+)	CRs (50%)	tsetse-frequented areas (52%)
Procedures	Minimum tsetse surface area for each year	Largest surface areas in targeting phase	Probability map of the whole study period
Purpose	Find tsetse infestation	Control	Exposure
Reasons	Tsetse reliably existed during study period	Tsetse reliably existed during targeting phase	Long term not seasonal; higher presence causes higher risk

3.3.2 Threshold for Population Density

For the identification of highly populated areas in the definition of beneficial control areas, the 2002 LandScan™ data requested from Oak Ridge National Laboratory was used to study the population distribution in Tanzania (ORNL, 2002). The census data are disaggregated into administrative levels by a LandScan algorithm which uses spatial analysis, imagery analysis technologies, and a multi-variable dasymetric modeling approach (Dobson et al., 2000; Bright, Rose, and Urban, 2012). Therefore, the LandScan^{TM} dataset presents the geographical distribution of population at 955.12m resolution. Each pixel in the image represented the number of population density in 912,254.214 square meters. Besides, as a comparison, 2002 Integrated Public Use Microdata Series, International (IPUMS-International) census data of Tanzania were downloaded from Minnesota Population Center (2015). Before the 2002 LandScan^{TM} data were used, the quality of the data was checked by comparing the population in each district (i.e. the second administrative level boundaries in Tanzania) calculated by the LandScan^{TM} with 2002 IPUMS data.

In order to determine the threshold for classifying highly populated locations for beneficial control areas, the population density and tsetse presence were first combined; the 250m tsetse probability map and 2002 LandScan^{TM} data were resampled in ArcMap 10.2 to 1 km resolution to match with each other. The relationship between the population density and frequency of tsetse appearance is described in the following scatterplot (Figure 3.8). For a better view, the selected part with the frequency of tsetse presence greater than 0.5 is enlarged. As shown in the enlarged figure, the blue line (x=0.52) is plotted, since the threshold to identify tsetse-frequented areas is 52% as previously described. The cases above the red line (y=1000) are suspended in the x-y plane, which suggests a relatively higher population density. However, the points with population density below 1,000 per km^2 (the red line) are mainly randomly distributed along the x-coordinate. Thus, the 1000 population density per km^2 is selected as the threshold to define the places with the highly population in terms of beneficial control areas. In summary, the points in Figure 3.8 located above the red line (y=1000) and right to the blue line (x=0.52) are the places with over 52% tsetse presence and population density over 1,000 per km^2, which are defined as the BCAs in this study.

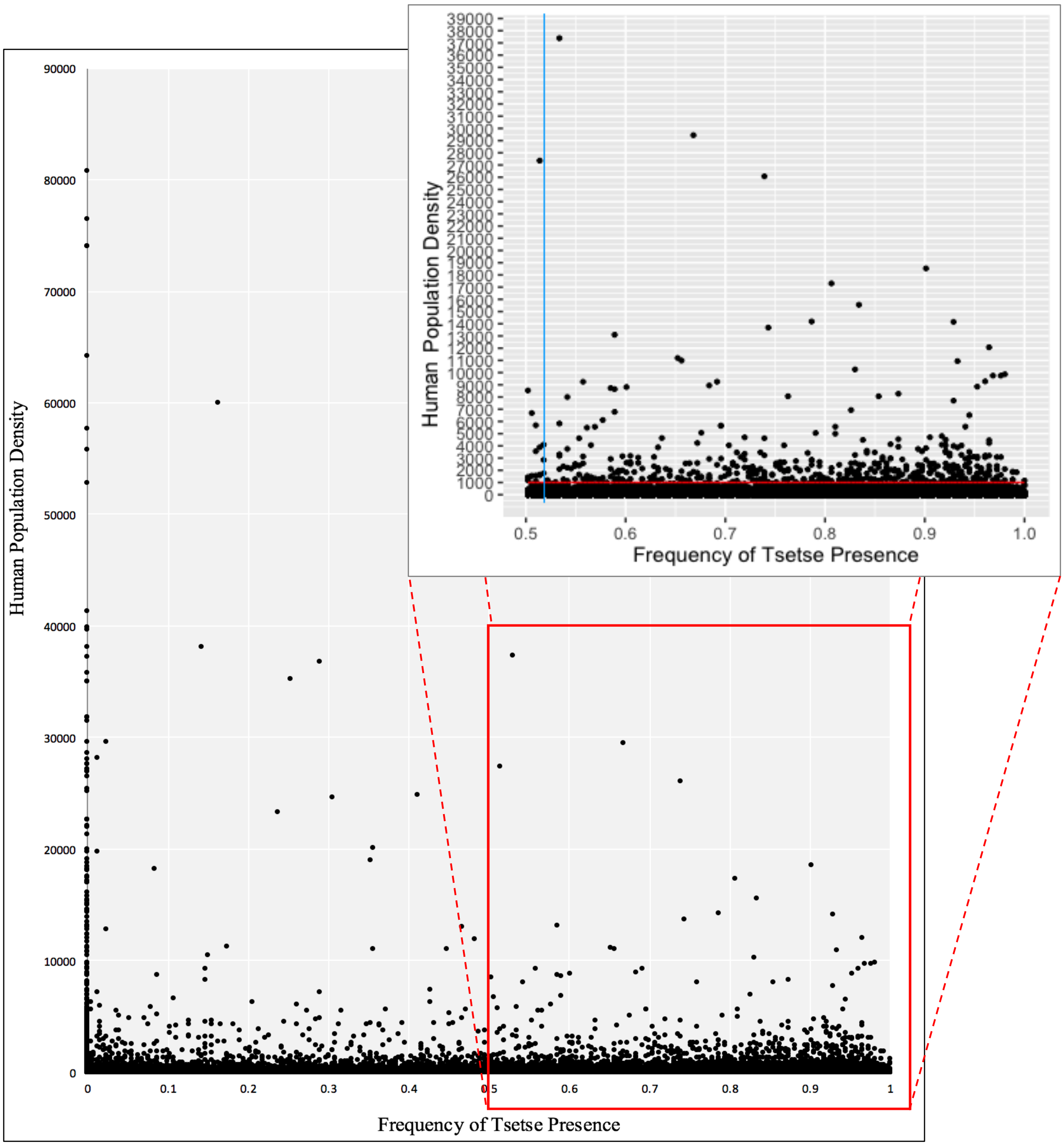


Figure 3.8: Scatterplot of human population density and frequency of tsetse presence. *The selected area is enlarged.*

CHAPTER 4

RESULTS

4.1 Tsetse Presence Probability Map

The tsetse presence probability map is shown in Figure 4.1. The spatial resolution of the output map is 250m, and the values of pixels in the map range from 0.0 to 1.0. Each pixel of the percent probability map represented the likelihood of encountering tsetse flies at any time during the study period from 2003 to 2013. The TED model only simulates areas with sustaining fly populations. There are likely some areas with lower densities outside of this map.

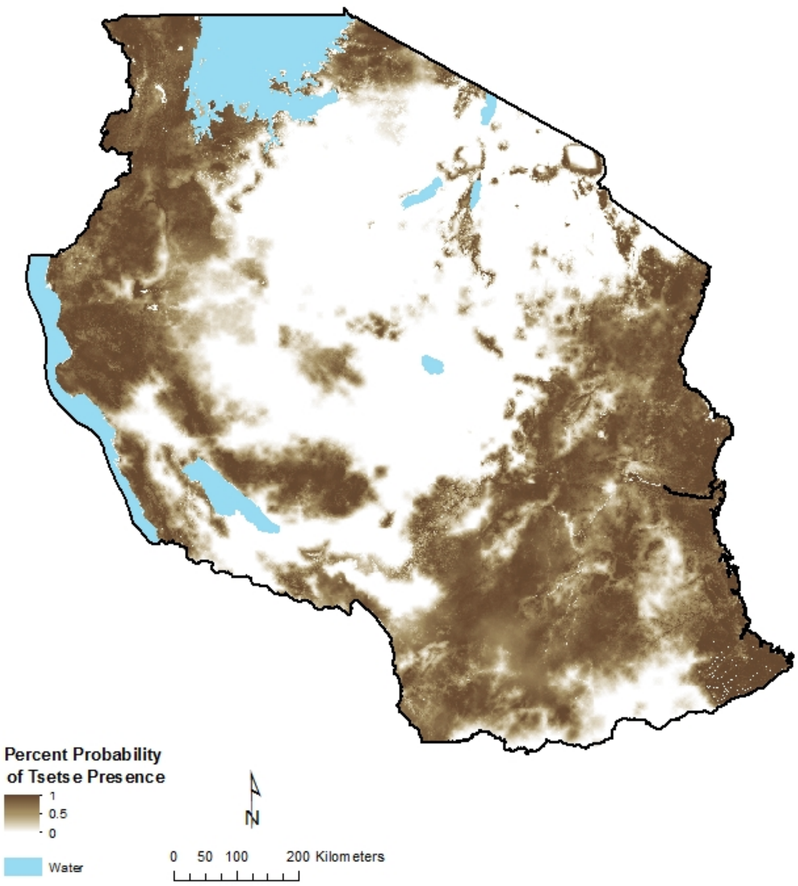


Figure 4.1: The percent probability of tsetse presence map generated by the TED model

4.2 Cost Analysis

The CRs and TZs in each belt are shown in Figures 4.2-4.4. The total areas of TZs and CRs except the ones removed from the cost analysis are 652,640.91$km^2$and 469,601.03km^2, respectively. The total cost for fly management campaign conducted in TZs is \$170,260,046 (USD), while the amount drops to \$ 116,585,329 (USD) in CRs.

4.2.1 Non-field Control Costs

The costs of non-field control tasks including administration, surveying and monitoring in the CRs and TZs are shown in Tables 4.1 and 4.2, respectively. The total costs of non-field control tasks in the CRs amount to \$ 56,754,619 (USD), but jump to \$ 75,383,950 (USD) in TZs. Therefore, it can help to save US\$ 19,262,235 if the seasonal variation of dynamic distributions is considered in non-field control activities. Since the size of the control area in AU, IAEA, and ADB (2004) document varied from 10,000km^2 to 40,000km^2, the number of inputs for each task has been adjusted to agree with the total CR area and the total TZ area (McCord, 2012). In the following tables, the costs of different the tasks have been discounted to their present value in the baseline year, Year 3, which is 2010 in this study. The two decimal places for Cost per km^2 and Total Cost per km^2 remain, because the cost per km^2 in sleeping sickness active case finding is less than \$1 (USD), which might be neglected due to rounding.

Table 4.1: *Non-field control (surveying, monitoring, and administration) costs of control reservoirs*

Year	Admin. & Office support	Ento. & Tsetse pop. genetics survey	Socioeconomic survey	Sleeping sickness survey	Parasitological and Serological Data Collection	Environ. Impact Assessment	Sleeping Sickness Active Case Finding	Environmental & Entomological Monitoring
1	$98,021	$13,621,523	$1,850,486	$0	$0	$0	$0	$0
2	$89,110	$1,377,977	$164,951	$828,027	$8,633,366	$2,528,251	$0	$0
3	$81,009	$538,385	$134,668	$104,434	$765,718	$421,418	$99,613	$5,533,910
4	$73,637	$402,028	$122,414	$70,500	$696,037	$382,642	$90,548	$5,134,778
5	$66,914	$365,319	$111,236	$64,085	$632,483	$346,539	$82,280	$4,787,050
6	$103,555	$90,664	$48,191	$0	$5,441,098	$99,761	$39,088	$632,904
Sub-total	**$512,247**	**$16,395,897**	**$2,431,946**	**$1,067,046**	**$16,168,702**	**$3,778,611**	**$311,528**	**$16,088,642**
Cost per km^2	**$1.09**	**$34.91**	**$5.18**	**$2.27**	**$34.43**	**$8.05**	**$0.66**	**$34.26**
Total Costs								**$56,754,619**
Total Cost per km^2								**$120.86**

Source: Adapted from AU, IAEA, and ADB (2004), Shaw et al. (2007) and McCord et al. (2012).

Notes: The total area of control reservoirs was 469,601.03km^2.

Table 4.2: *Non-field control (surveying, monitoring, and administration) costs of tsetse zones*

Year	Admin. & Office support	Ento. & Tsese popu. genetics survey	Socioeconomic survey	Sleeping sickness survey	Parasitological and Serological Data Collection	Environ. Impact Assessment	Sleeping Sickness Active Case Finding	Environmental & Entomological Monitoring
1	$98,021	$18,885,427	$2,559,642	$0	$0	$0	$0	$0
2	$89,110	$1,903,499	$228,542	$1,041,040	$11,510,761	$2,651,910	$0	$0
3	$81,009	$746,275	$186,853	$131,300	$669,052	$427,183	$99,613	$7,725,755
4	$73,637	$558,967	$169,849	$88,628	$583,549	$387,118	$90,548	$7,195,204
5	$66,914	$507,928	$154,340	$80,535	$519,080	$350,148	$82,280	$6,708,252
6	$103,555	$95,297	$67,104	$0	$7,489,389	$19,129	$39,088	$890,067
Sub-total	**$512,247**	**$22,697,393**	**$3,366,329**	**$1,341,503**	**$20,771,831**	**$3,835,487**	**$311,528**	**$22,519,278**
Cost per km2	**$0.78**	**$34.77**	**$5.16**	**$2.05**	**$31.83**	**$5.87**	**$0.48**	**$34.50**
Total Costs								**$75,383,950**
Total Cost per km2								**$115.49**

Source: Adapted from AU, IAEA, and ADB (2004), Shaw et al. (2007) and McCord et al. (2012).

*Notes: The total area of tsetse zones was 652,640.91*km^2.

In the non-field control activities, the Entomological Survey and Tsetse Fly Population Genetics Survey are the costliest for both CRs and TZs. It is not surprising since this task includes the trapping and sampling of the flies, as well as the study of fly genetics. Environmental and Entomological Monitoring is also an expensive task, since it occurs each of the years that field control operations are taking place (i.e. Year 3, Year 4, Year 5). Similarly, the Parasitological and Serological Data Collection task, performed in Years 2 and 6, is costly.

4.2.2 Field Control Costs

For the field control, the total costs to eradicate tsetse flies in the CRs sum to US$ 60,641,924.78, but the costs grow to US$ 94,876,096.30 in TZs. The total savings of US$ 34,234,171.52 is achieved if the field control tasks occurred in the CRs. The detailed costs of each task in CRs and TZs are given in the following tables (Table 4.3 and 4.4)

Table 4.3: *Field control costs of control reservoirs*

Year	Eastern Great Lake Region Belt (Belt2)	Western Tanzania & Great Lake Region Belt (Belt1)	Coastal & Central Tanzania Belt (Belt3)	Total Costs
1	$0	$0	$0	$0
2	$0	$0	$0	$0
3	$3,354,930	$0	$0	$3,354,930
4	$122,315	$22,647,131	$0	$22,769,446
5	$111,147	$1,365,535	$28,830,101	$30,306,783
6	$100,859	$1,239,976	$2,058,716	$3,399,552
Total	**$3,689,250**	**$25,252,642**	**$30,888,817**	**$59,830,710**
Cost per km^2	**$187**	**$148**	**$111**	**$127**

Source: Adopted from Shaw et al. (2007) and McCord et al. (2012).

Notes: the total area of control reservoirs is 469,601.03 km^2.

Cost per km^2 *used the total CRs in each belt: Western Tanzania & Great Lake Region Belt (Belt1), 247,625.7*km^2*; Coastal & Central Tanzania Belt (Bel2), 355,899.01*km^2*; Eastern Great Lake Region Belt (Belt3), 49,116.2*km^2.

Table 4.4: *Field control costs of tsetse zones*

Year	Eastern Great Lake Region Belt (Belt2)	Western Tanzania & Great Lake Region Belt (Belt1)	Coastal & Central Tanzania Belt (Belt3)	Total Costs
1	$0	$0	$0	$0
2	$0	$0	$0	$0
3	$8,633,541	$0	$0	$8,633,541
4	$373,890	$36,834,739	$0	$37,208,629
5	$339,750	$1,973,165	$42,318,799	$44,631,715
6	$308,511	$1,791,736	$2,301,965	$4,402,212
Total	**$9,655,692**	**$40,599,640**	**$44,620,764**	**$94,876,096**
Cost per km²	**$197**	**$164**	**$125**	**$145**

Source: Adopted from Shaw et al. (2007) and McCord et al. (2012).

Notes: the total area of tsetse zones is 652,640.91 km2.

Cost per km^2 *used the following TZ areas in each belt: Western Tanzania & Great Lake Region Belt (Belt1), 171,059.44* km^2 *; Coastal & Central Tanzania Belt (Bel2), 278,801.82*km^2*; Eastern Great Lake Region Belt (Belt3), 19,739.77*km^2.

In order to control the seasonally constrained distribution of tsetse flies, determining the exact date to start the targeting phase is of great importance. This date is defined as the first day of the formation of the CRs during the minimum area interval (McCord et al., 2012). The minimum interval is described previously as the 216 continuous days when tsetse flies occupied the least area. In order to ensure the enough time for 216-day control period during each year, the field control in each control administrative unit (i.e. TZs and their CRs) should at least begin by the 145th day of the year (May 25). Since the beginning date for tsetse control might be different in different years, the most frequent date during the study period of 11 years is chosen to start the control tasks in the field. Following this rule, the selected starting date of the targeting phase might be different for different TZs and their CRs. In this study, the result suggests that the all the TZs and their CRs have the same day to start targeting phase, which is May 25. Figures 4.2-4 show examples of the selection of starting date for field control in one TZ of each belt. This is not surprising given that May 25 also corresponds with the end of the long rainy season (McCord, 2012). The dynamic tsetse distribution shows a significant decrease of tsetse infested areas during the cool dry season.

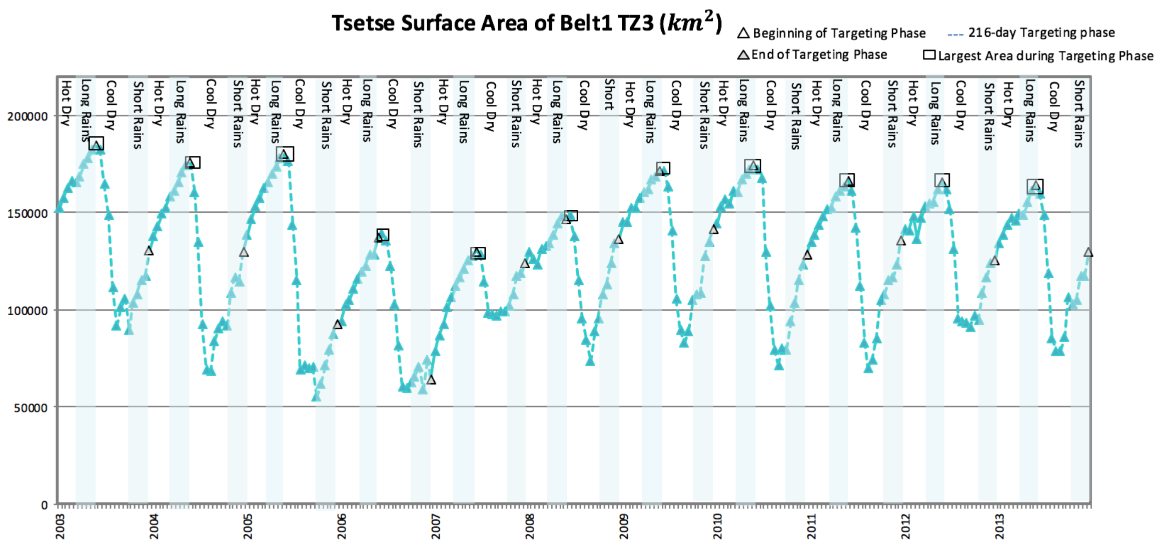


Figure 4.2: Tsetse Surface Areas in a TZ I. *This figure shows tsetse distribution areas for tsetse zone three in the Western Tanzania & Great Lake region (Belt1) with the starting and ending date for targeting phase*

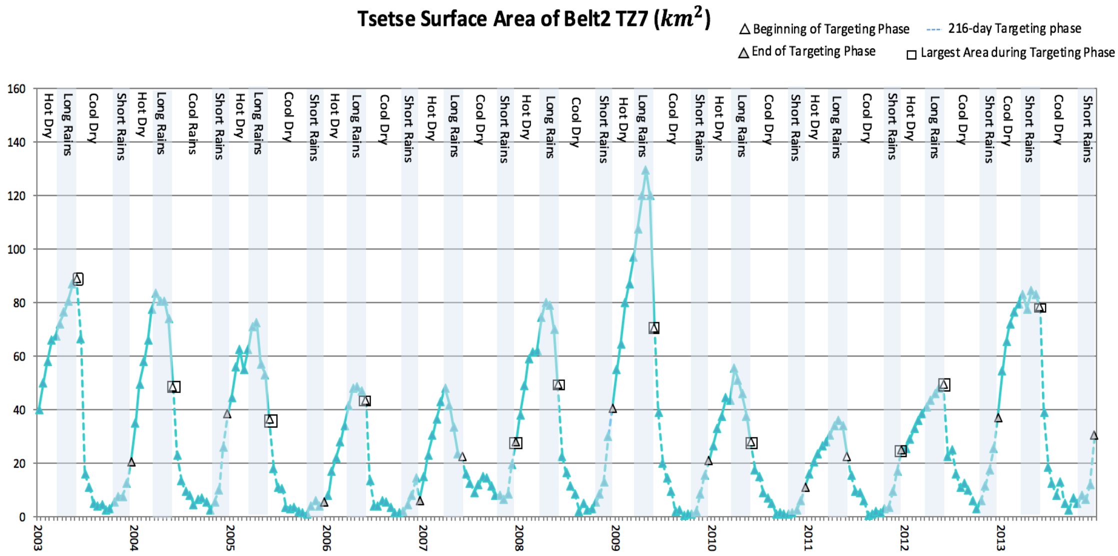


Figure 4.3: Tsetse Surface Areas in a TZ II. *This figure shows tsetse distribution areas for tsetse zone seven in the Eastern Lake Victoria region (Belt2) with the starting and ending date for targeting phase*

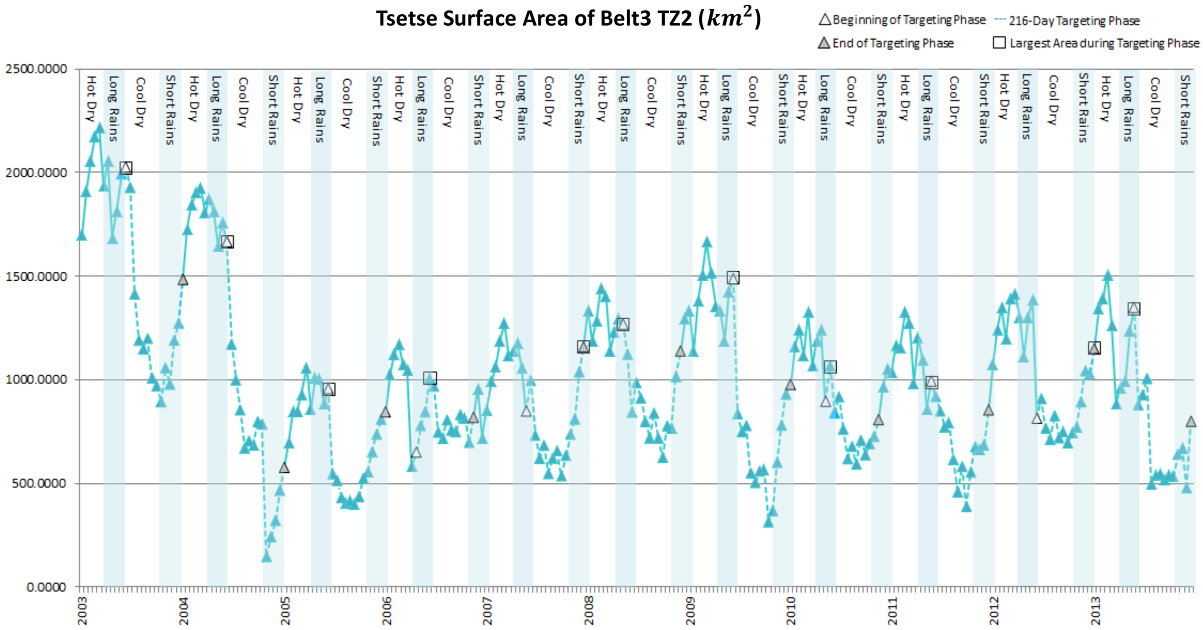


Figure 4.4: Tsetse Surface Areas in a TZ III. *This figure shows tsetse distribution areas for tsetse zone seven in the Coastal &Southern Tanzania region (Belt3) with the starting and ending date for targeting phase*

4.1.2.1 Eastern Lake Victoria Region Belt

Table 4.5 lists a summary of capital and labor inputs for CRs and TZs for Eastern Great Lake Region Belt during the targeting phase. The areas for each CR and TZ are given in Figure 4.5. Since the predicted tsetse distribution surface areas of TZ1, TZ4, TZ5 and TZ6 fall to zero before the study period, these TZs have been removed from this analysis, but are still mapped in Figure 4.3. The total cost of tsetse control in the field in CRs of the Eastern Great Lake Region Belt is \$ 3,689,250 (USD), and grows to \$ 9,655,692 (USD) in TZs. It would save \$ 5,966,441 (USD) if the control operations were carried out in the CRs of this belt.

Table 4.5: *Eastern Lake Victoria Region Belt: Summary of capital and labor inputs in targeting phase*

Items	CR Inputs / TZ Inputs							
	CR2	**CR3**	**CR7**	**CR8**	**CR9**	**CR10**	**CR11**	**CR12**
	TZ2	**TZ3**	**TZ7**	**TZ8**	**TZ9**	**TZ10**	**TZ11**	**TZ12**
Targets	73832	958	209	16	135	360	503	16368
	139996	8752	2434	1642	1328	2644	3087	69978
4*4 Vehicle	16	1	1	1	1	1	1	4
	31	1	1	1	1	1	1	15
Team Leaders	16	1	1	1	1	1	1	4
	31	1	1	1	1	1	1	15
Laborers	128	8	8	8	8	8	8	32
	248	8	8	8	8	8	8	120
Deltameth.(L)	563	7	2	0	1	3	4	125
	1068	67	19	13	10	20	24	534
Octenol(Sachets)	18931	246	54	4	35	92	129	4197
	35896	2244	624	421	341	678	792	17943
Acetone(L)	189313	2456	536	41	346	923	1290	41969
	358964	22441	6241	4210	3405	6779	7915	179431
Camping Eq.	128	8	8	8	8	8	8	32
	248	8	8	8	8	8	8	120

Notes: TZ1, TZ4, TZ5, and TZ6 have been removed since the tsetse density in these areas fell to zero before the end of the study period. "Deltameth." is the abbreviation of deltamethrin.

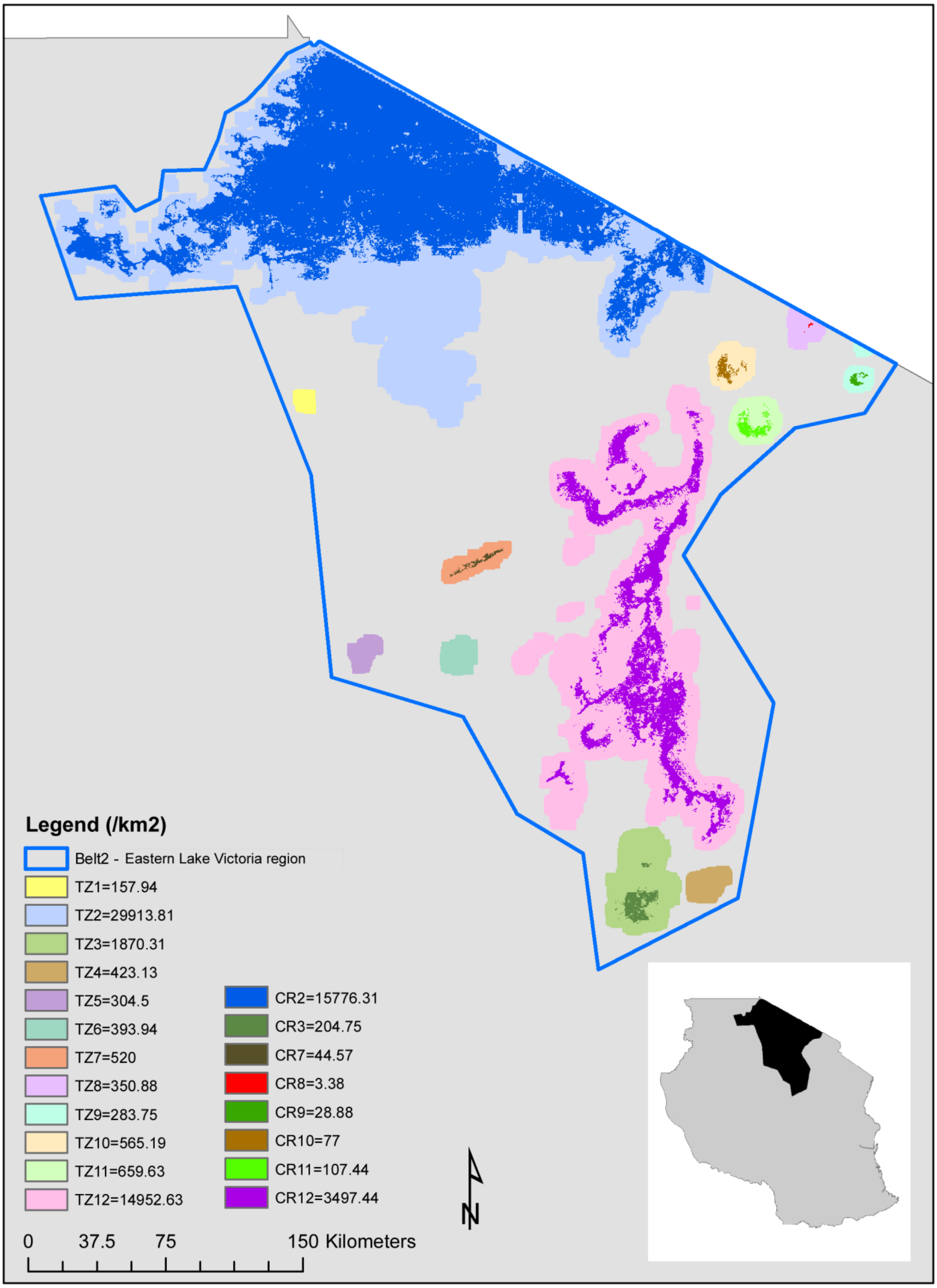


Figure 4.5: Surface areas of CRs and TZs in Eastern Lake Victoria region Belt

4.1.2.2 Western Tanzania & Great Lake Region Belt

Table 4.6 gives a summary of capital and labor inputs for CRs and TZs for Western Tanzania & Great Lake Region Belt during the targeting phase. The areas for each CR and TZ are provided in Figure 4.6. TZ2, TZ6, and TZ7 mapped in the figure have been removed from this analysis, because the tsetse density in these tsetse zones fell to zero before the end of the study period. The TZ1 has a low frequency of tsetse presence (less than 50 percent), so there is no CR in this tsetse zone. The total cost of field control in CRs of the Western Tanzania & Great Lake Region Belt accounts to \$ 25,252,642 (USD), while in TZs sums to US\$ 40,599,640 (USD). The total savings of US\$15,346,998 (USD) would be achieved, if the field control tasks took place in the CRs in Western Tanzania & Great Lake Region Belt.

Table 4.6: *Western Tanzania & Great Lake Region Belt: Summary of capital and labor inputs in targeting phase*

Items	**CR Inputs**			
	TZ Inputs			
		CR3	**CR4**	**CR5**
	TZ1	**TZ3**	**TZ4**	**TZ5**
Targets		767006	26618	6934
	2100	1064535	57909	34345
4*4 Vehicle		200	7	2
	1	277	15	9
Team Leaders		200	7	2
	1	277	15	9
Laborers		1598	56	14
	8	2216	120	72
Deltameth.(L)	0	5853	203	53
	16	8124	442	262
Octenol(Sachets)	0	196668	6825	1778
	538	272958	14848	8806
Acetone(L)	0	1966682	68251	17779
	5385	2729577	148485	88064
Camping Eq.		1598	56	14
	8	2216	120	72

Notes: TZ1, TZ4, TZ5 and TZ6 have been removed since the tsetse density in these areas fell to zero before the end of the study period. "Deltameth." is the abbreviation of deltamethrin.

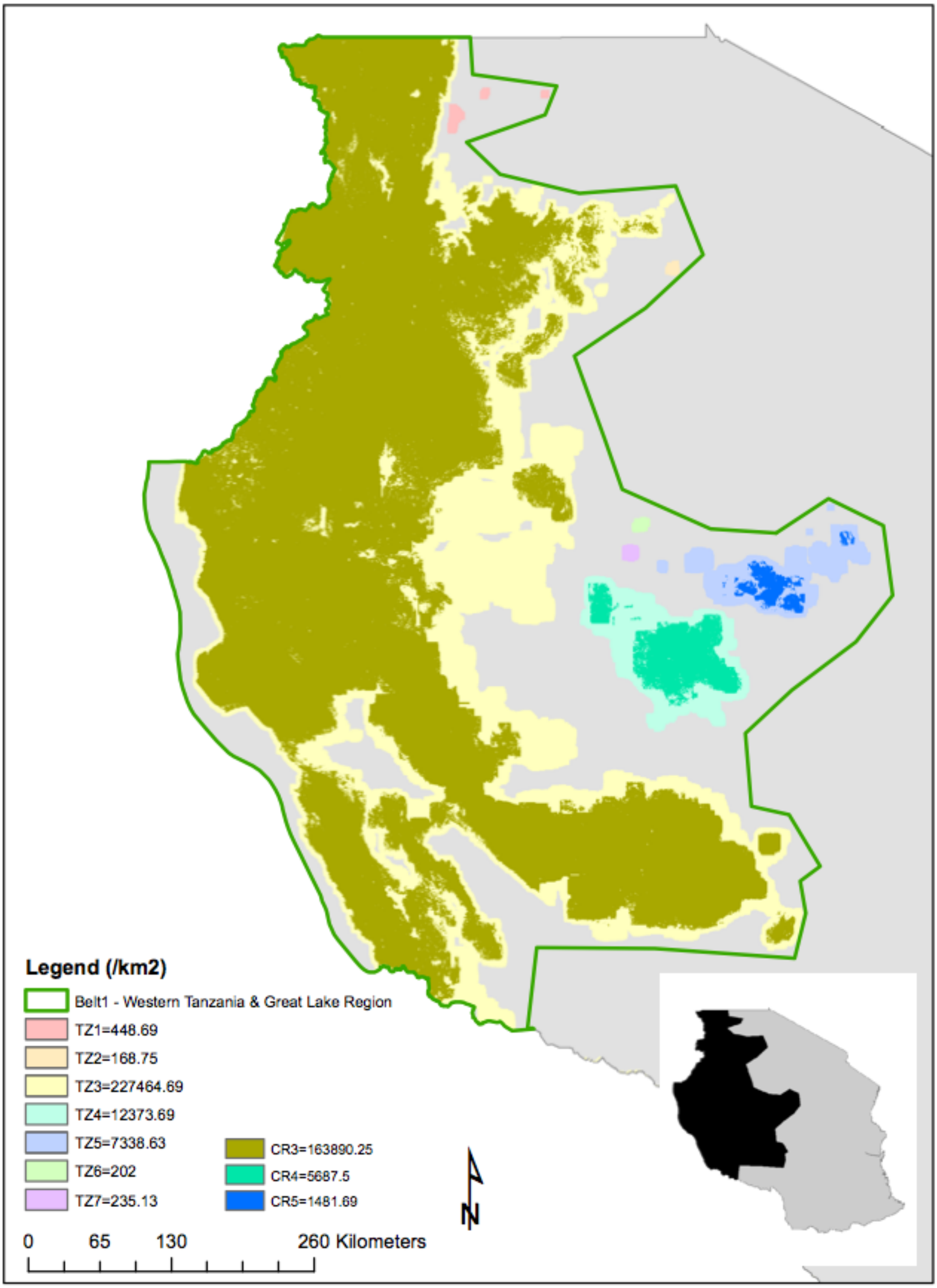


Figure 4.6: Surface areas of CRs and TZs in Western Tanzania & Great Lake Region Belt

4.1.2.3 Coastal & Southern Tanzania Belt

Table 4.7 lists a summary of capital and labor inputs for CRs and TZs for Coastal & Central Tanzania Belt during the targeting phase. The areas for each CR and TZ are provided in Figure 4.7. In this belt, TZ4, TZ5, TZ7 and TZ8, mapped in the figure have been excluded, because the tsetse density in these tsetse zones fell to zero during the study period. The total cost of eliminating tsetse flies in the field in CRs of the Coastal & Central Tanzania Belt is $ 30,888,817 (USD), while in TZs amounts to $ 44,620,764 (USD). The cost of $ 13,731,947 (USD) can be saved, when controlling the tsetse flies in the CRs of this belt in the field.

Table 4.7: *Coastal & Southern Tanzania Belt: Summary of capital and labor inputs in targeting phase*

Items	CR Inputs / TZ Inputs			
	CR1	CR2	CR3	CR6
	TZ1	TZ2	TZ3	TZ6
Targets	1298818	3580	136	2359
	1637852	10253	1262	16240
4*4 Vehicle	289	1	1	1
	364	2	8	4
Team Leaders	289	1	1	1
	364	2	1	4
Laborers	231	6	8	4
	2912	16	8	32
Deltameth.(L)	9911	27	1	18
	12499	78	10	124
Octenol(Sachets)	33287	918	35	605
	419962	2629	324	4164
Acetone(L)	332867	9179	349	6049
	4199621	26290	3236	41641
Camping Eq.	231	6	8	4
	2912	16	8	32

Notes: TZ4, TZ5, TZ7 and TZ8 have been removed since the tsetse density in these areas fell to zero before the study period. "Deltameth." is the abbreviation of deltamethrin.

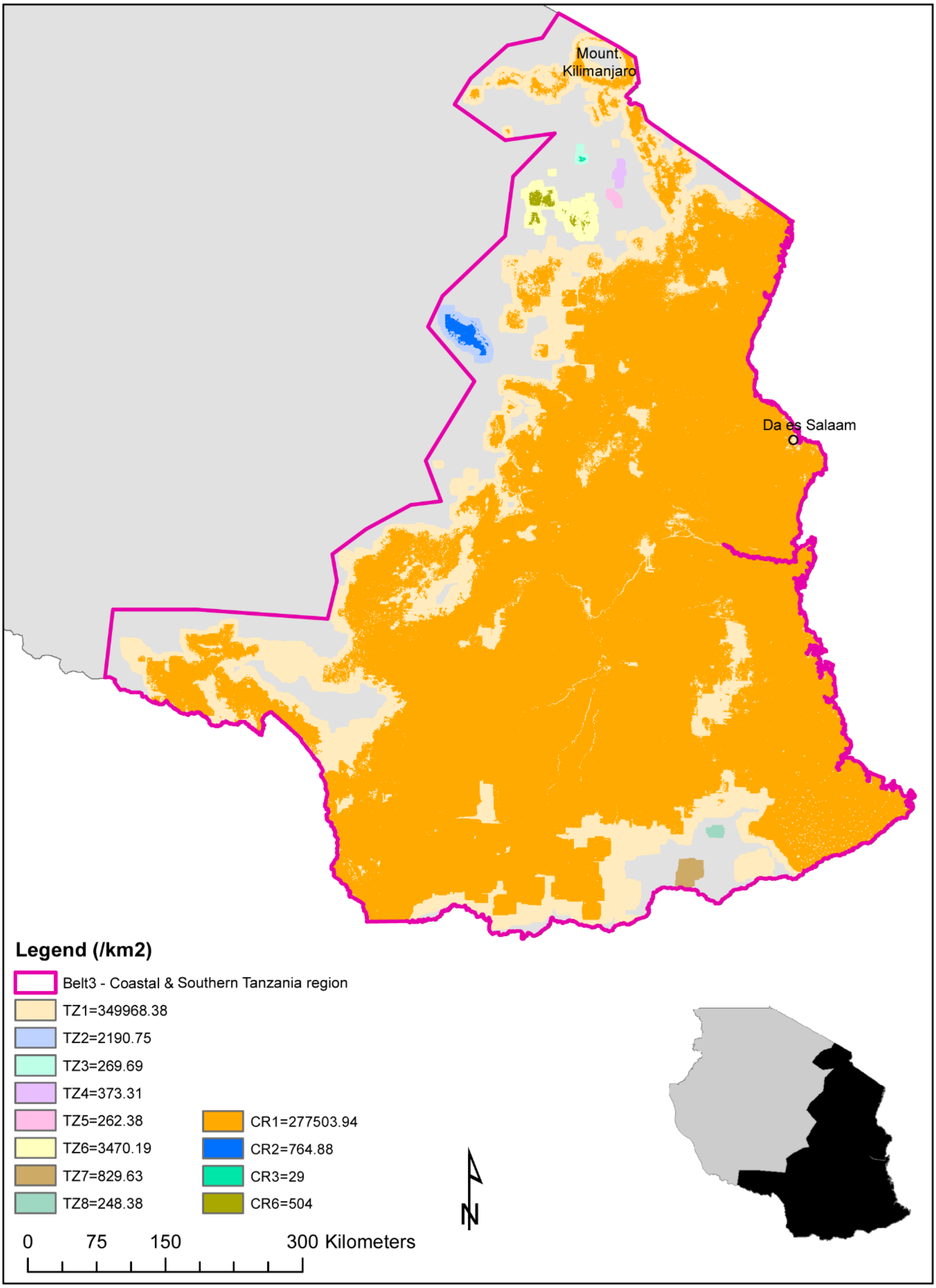


Figure 4.7: Surface areas of CRs and TZs in Coastal & Southern Tanzania Belt

4.3 Results for Cost Benefit Analysis

The two criteria were described previously in Section 3.3 to identify the BCAs (i.e. the areas with population density over 1000 and percent of tsetse presence over 52%). The results show that there are 484 1km*1km pixels identified as BCAs mapped in Figure 4.8, and the hot spots are detected by kernel density estimation (KDE) with the optimal bandwidth at 6113.014 in R shown in Figure 4.9. Here, the bandwidth was calculated with a cross-validation approach (i.e. bw.diggle() function of "spatstat" package in R (Baddeley and Turner, 2005)). The function evaluates different bandwidths and selects the one which minimizes the mean squared error as the optimal bandwidth, via the criterion proposed by Peter Diggle (1985). According to the two maps, the hot spots are generally located along the shore of Lake Victoria, in the areas surrounding Mkomazi national park and Mount Kilimanjaro, as well as the southeast corner of the country.

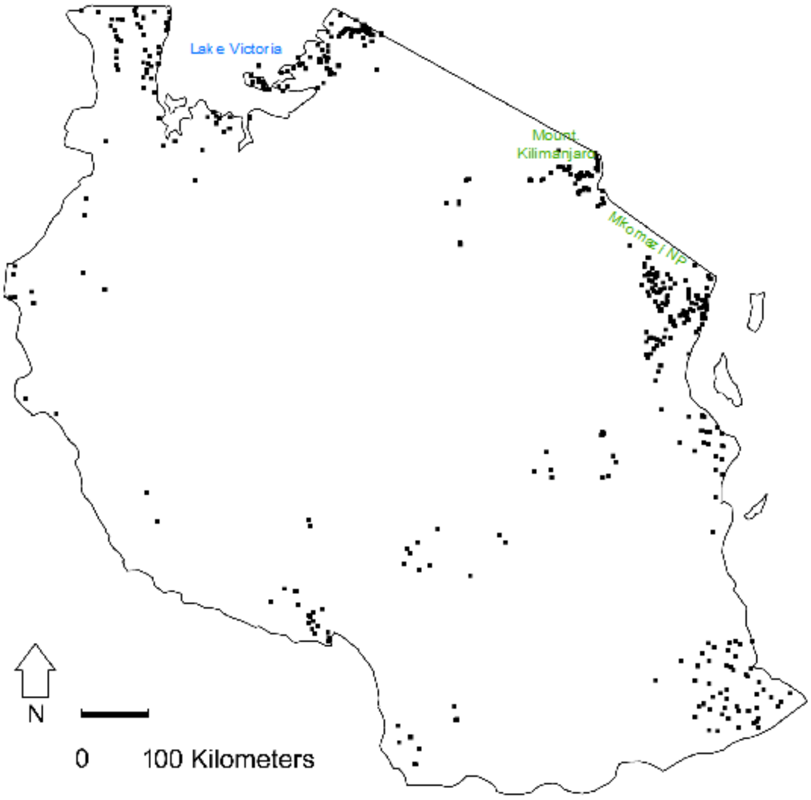


Figure 4.8: Spatial distribution. *This figure shows the spatial distribution of BCAs*

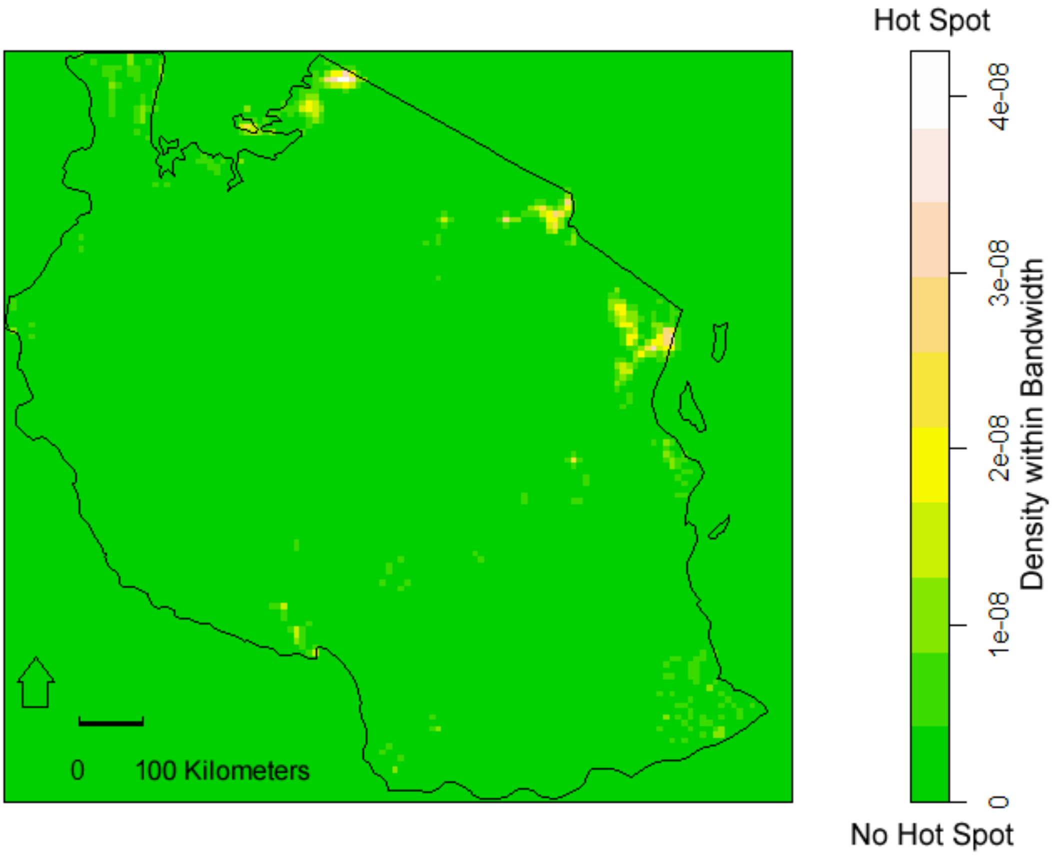


Figure 4.9: Kernel density map. *This hot spots of BCAs are identified in the map*

CHAPTER 5

DISCUSSION AND CONCLUSION

5.1 Discussion

The spatial pattern of the BCAs is a result of interacting environmental, social, and geographical determinants that affect the overlaps of the human and tsetse habitats. To first study the geographical characteristics of the BCAs, the land cover types were detected using the following method. The 2013 MODIS Land Cover Type 1 classification was resampled from a resolution of 500m to 1km, matching the resolution of the resampled 2002 Landscan^{TM} population data and the resampled TED model probability map. The values of the resampled Land Cover data were extracted and recorded as an attribute table of the point feature class for the identified beneficial control areas. The pixel numbers for each land type are summarized and tabulated in the Table 5.1. Among the land types shown in the table, Evergreen Broadleaf forest, Deciduous Broadleaf forest, Mixed forest, Woody savannas, Savannas, Permanent wetlands and Cropland/Natural vegetation mosaic are suitable for the tsetse fly. And most BCAs are located in the three typical land types (i.e., mixed cropland/Natural vegetation regions, savannas, and woody savannas). However, the resampling of the 2013 Land Cover data inevitably causes a loss of accuracy resulting in some misclassifications of land types. For example, open water should not be included in the highly populated areas, and there should be no tsetse flies existing in urban areas, croplands and grasslands.

Table 5.1: *Pixel numbers of beneficial control areas for each land cover type*

Type of Land	Pixel Numbers
Water	1
Evergreen Broadleaf forest	10
Deciduous Broadleaf forest	1
Mixed forest	4
Woody savannas	52
Savannas	244
Grasslands	28
Urban and built-up areas	10
Permanent wetlands	2
Croplands	14
Cropland/Natural vegetation mosaic	196

To analyze the environmental and social driving forces that influence the distribution of the BCAs, it is of primary necessity to study the land use within and surrounding them. The original 2013 Land Cover Type classification with 500m resolution is used to map the relationship between land covers and beneficial control areas in Figure 5.1. With the BCAs defined as the overlaps of human habitats and tsetse-infested areas, the selection of land type classifications in the map should include both the suitable land cover for tsetse flies and potential human activities. For the land covers determining the tsetse infestation, three specific land types (i.e. mixed cropland/Natural vegetation regions, savannas, and woody savannas) are selected in the map (Figure 5.1). These land covers represent the common geographical characteristics of BCAs and are suitable to support the survival of tsetse flies. However, these savannas and woody savannas are not ideal habitats for human settlement. Therefore, it is important to include the land cover types that indicate potential human activities, such as the croplands, urban and built-up areas, as well as grasslands. These three land types support food production and livestock grazing and indicate potential human activities. Studying the distribution of the BCAs and the land covers related with human activities and tsetse habitat can help to understand the human-fly interactions, so as to explain the factors that affect the spatial pattern of the BCAs.

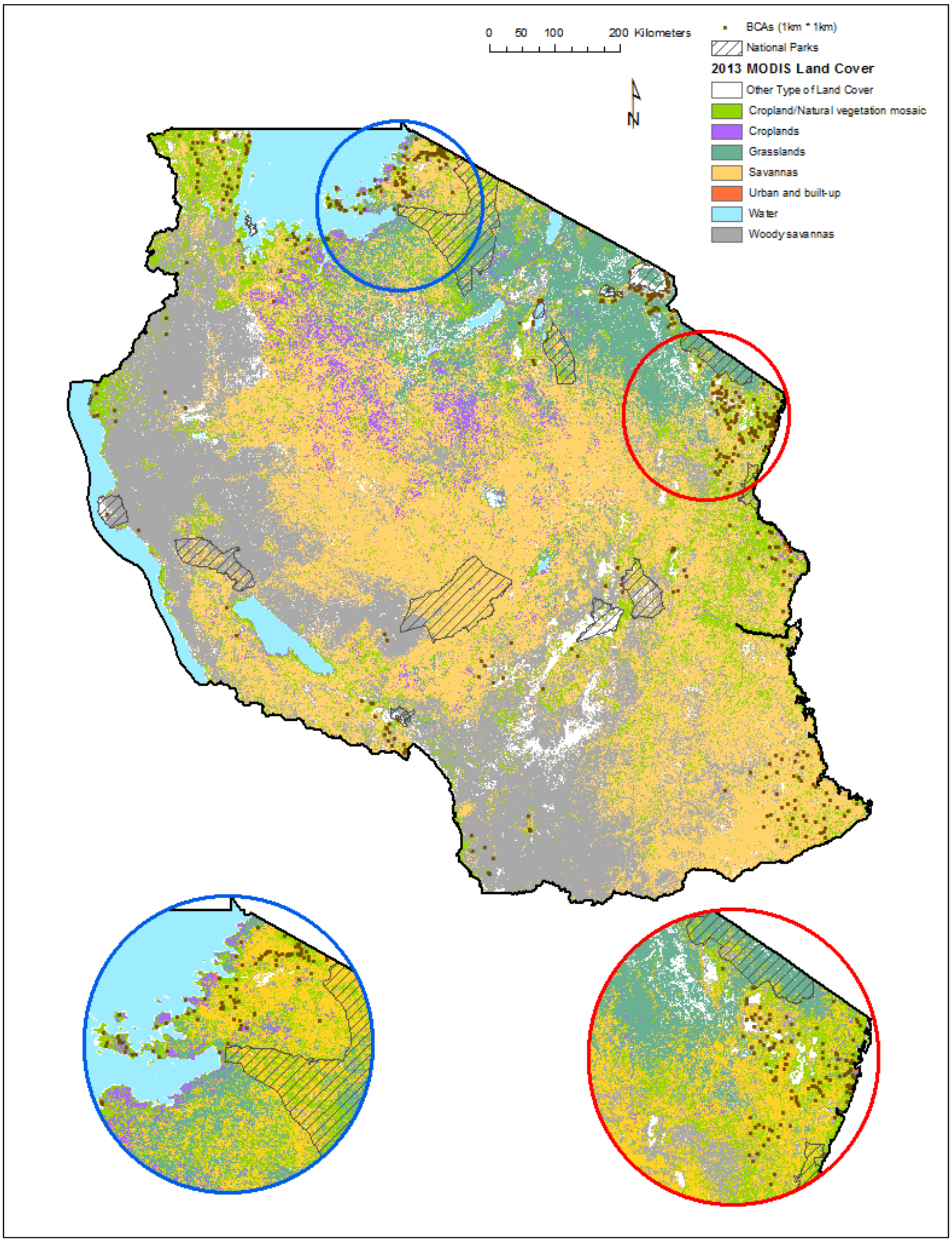


Figure 5.1: BCAs and land covers. *Distributions of beneficial control areas and land cover types are shown in map*

The dominant factors affecting the formation of each hotspot in the distribution of the BCAs are analyzed with respect to socioeconomics, human activities near tsetse habitat, historical tsetse distribution. The Lake Victoria cluster supports the largest inland fishery in Africa, with fishing and fish processing as one of the important economic activities for millions of people in the basin (Balirwa et al., 2003). The complex and mixed land types surrounding the lake are shown in Figure 5.1. Grasslands, croplands and urban areas suggest potential human activities in these places. Most of these human habitats are mixed with the tsetse suitable habitat with woody vegetation. Furthermore, it has been recorded that tsetse flies infested within Lake Victoria regions (Worboys, 1994; Wint, 2001). Before Tanzanian independence, Sese Islands in the lake were regarded as one of the most heavily infested areas. A scientific mission was sent to the islands in 1906 to isolate the patients and treat on them with a variety of arsenic-based compounds (Clyde, 1962; De Ville, 1989; Headrick, 2014). Despite the control campaigns carried out in the Lake Victoria basin for centuries, a recent research still showed that *G. f. fuscipes* was widely distributed along the shore extending from northwestern Tanzania (Uganda border) to the northeastern Tanzania (Kenya border) (Manangwa et al., 2015). This recent study was conducted in Msozi village in Ukerewe district and Kemondo village in Bukoba Rural district, as well as Kirongwe, Rasi Nyabero, Masonga, and Tobwe River villages in Rorya district (Manangwa et al., 2015). The tsetse fly was found in all visited small Islands like Ngonshe and Bugambwa in Suba division in Rorya district in Musoma (Manangwa et al., 2015). The big Ukerewe Island in Mwanza region was also found to be tsetse infested (Manangwa et al., 2015). The locations of the districts and villages (study sites) are shown in Figure 5.2.

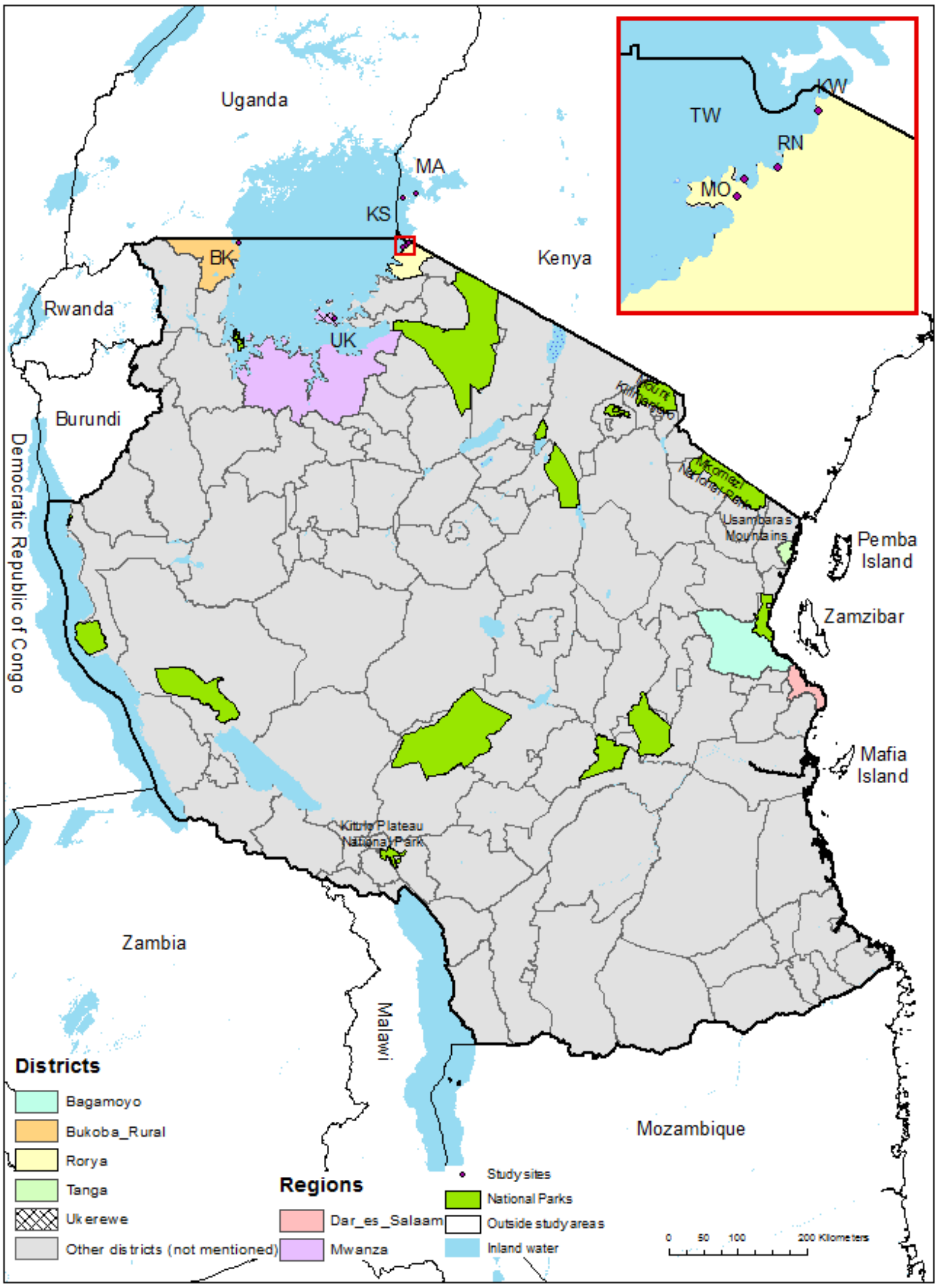


Figure 5.2: Reference map. *This map shows locations for regions, districts and villages of Tanzania mentioned in this section (Adopted from Manangwa et al., 2015)*

Second, some of the BCAs are peri-urban, such as the group of cases at the southeastern corner of the country and the cases surrounding Dar es Salaam. Although tsetse flies are never found in dense urban areas, transmission of trypanosomiasis has been reported in peri-urban areas (Grébaut et al., 2009; WHO, 2016). In developing countries, peri-urban agriculture plays an important role in feeding the growing urban populations (Makita et al., 2010). But these areas also carry public health risks for zoonotic disease transmission (Makita et al., 2010). In Tanzania, most of the urban areas and cities are distributed along the coastline. Given the land pressure caused by dramatically increasing urban populations, livestock keepers in urban areas often relocate to peri-urban areas. For example, farmers with 25,000 dairy cattle in Dar es Salaam were moved to peri-urban coconut plantations in Bagamoyo districts in 1997 (the location of regions and districts shown in Figure 5.2) (Njau, 2000). If the peri-urban places are also located within or near the suitable habitats of tsetse flies, increasing trypanosomiasis risk results.

Third, some of the beneficial areas for tsetse control are close to some national parks or forest conservations, including the cluster of points surrounding Mount Kilimanjaro National Park, the one near Mkomazi National Park, and the sparsely distributed cases south to Kitulo Plateau National Park. These national parks provide a large number of wild animals not only as the reservoir hosts for *trypanosoma* but also as the sources of blood meal for tsetse fly. The national parks usually tend to be the permanent suitable tsetse habitats. In Mkomazi National Park, which is connected with Tsavo National Park in Kenya, the dominant vegetation is Acacia-Commiphora bush, woodland and wooded grassland (Suttie, Reynolds, and Batello, 2005). The extensive grasslands within and surrounding Mkomazi are especially valuable to pastoralists. Briggs (2006) reported a significant growth of settlements along the periphery of Mkomazi National Park. Currently, many small villages are located from the southeast corner of the Mkomazi National Park to Tanga District, especially around Usambaras Mountains. Increasing populations have been reported living in the Usambaras

Mountains, another forest conservation, since the 1967 census (Lundgren, 1980). The population pressure in this area has subsequently intensified the pressure on farming land, thus lead to the clearing of forests (Hamilton and Bensted-Smith, 1989). Nowadays, the population growth rates in these areas are still high. As shown in the screen shot (see Figure 5.3), there are some villages and small towns with inter-mixed agricultural lands and woody vegetation. The surrounding land covers with woody vegetation indicate potential tsetse habitats.

Figure 5.3: Screen shot I. *Google Maps satellite image around Usambaras Mountains in Tanga Region (Google Maps, 2016)*

For the Mount Kilimanjaro National Park and Kitulo Plateau National Park, the typical volcanic soils on the mountain are of high agricultural potential (Sarwatt and Mollel, 2006). These soils are notable for the production of forage for dairy cattle at high or medium altitudes. As shown in the Google Maps satellite image (Figure 5.4), there are many small towns and villages distributed on the mountain outside Mount Kilimanjaro National Park. These residential areas are surrounded by the suitable tsetse habitats. However, both the Mount Kilimanjaro National Park and Kitulo Plateau National Park are reported to be tsetse-free areas, given the temperature limits (Spinage, 2012; Muse et al., 2015). Therefore, the likelihood of tsetse infestation along the periphery of these national parks should be low. Consequently, although potential BCAs near the Mount Kilimanjaro National Park and the Kitulo Plateau National Park were identified in this study, the actual BCAs may not exist nor need control.

Figure 5.4: Screen shot II. *Google Maps satellite image surrounding the Mount Kilimanjaro National Park (Google Maps, 2016)*

Whether to control tsetse flies inside the national parks is still a controversial issue. Tanzania's booming tourism industry has been driven largely by its national parks. 39 cases of human trypanosomiasis were reported from 2000 to 2010 among nearly 6 million non-resident tourists visiting national parks in Tanzania (Simarro et al., 2011; NBS, 2013). Some records also showed that six local residents contracted HAT in Serengeti National Park between 2001 and 2008 (Muse et al., 2015). Regarding the cost-benefit balance, the low rate of sleeping sickness cases reported inside the national parks suggests the limited benefits of tsetse control inside the parks. Moreover, owing to ecological and environmental concerns, controls in the park are contentious. However, from the perspective of broad tsetse elimination, the parks and game conservation areas provide a source of the perpetual infestation, thus making the eradication from the tsetse flies unlikely. Some studies suggest that the environmental damage of tsetse control activities do not threaten the survival of rare flora and fauna, and thus the control in the parks is supported (Reid et al., 1997; Muse et al., 2015).

5.2 Conclusion

5.2.1 Summary of Results

African trypanosomiasis is classified as the WHO neglected tropical disease with an estimation of 13,000 new human cases each year (CDC, 2008a / 2008b; DeVisser, 2009). This disease poses a risk for both humans and domestic livestock, and depresses agricultural development in endemic African countries. Currently, there is no vaccine to prevent infection, and trypanocidal drugs are toxic (CDC, 2012). Therefore, most of the efforts to control the disease have focused on controlling the tsetse fly, thus reducing the exposure potential (DeVisser, 2009).

This study has emphasized that funding sources for the tsetse control campaigns are limited. Given the clustering of the human population in Tanzania, the research was motivated by a need to maximize the cost-benefit relationship. The distribution of tsetse flies in Tanzania was simulated by TED model from 2003 to 2013. The dynamic tsetse distribution showed roughly regular fluctuations following a seasonal pattern: the habitat contracted during dry seasons and expanded in rainy seasons. The habitats reduced to a minimum during the cool dry season. The total costs for fly management were minimized by conducting control activities at suitable habitats during minimum area intervals (i.e. CRs). The resulting control costs showed a significant reduction when the control activities occurred in CRs. The total cost for fly management campaign was $ 116,585,329 (USD) in CRs, while it increased to $ 170,260,046 (USD) in TZs. The total of $ 53,674,717 (USD) would be saved, if the tsetse control campaigns took place in CRs. In order to maximize the benefits of tsetse control campaigns through the maximum reduction of potential exposures, the beneficial control areas were identified by the areas with population density over 1000 per km^2 and percent of tsetse presence above 52%. The result showed 484 1km*1km places as the BCAs. The spatial pattern of these points suggested second-order clustering with hotspots located along the shore of Lake Victoria, near the national parks and along some peri-urban areas.

5.2.2 Limitations

This study also had some limitations. For the TED model, the tsetse probability map does not present fly population density information, which is often more useful for tsetse control efforts (DeVisser et al., 2010). It would be highly promising if the optimal locations and the estimated numbers of flies could be provided to fly management officials (DeVisser et al., 2010). The TED model considers only the environmental and climatic conditions for tsetse survival, however, the distribution of the tsetse fly is also influenced by some other factors, such as the presence of suitable hosts and sex ratio of the fly (Majekodunmi et al., 2013). Besides, the quality of MODIS products used in the model directly influences the model results. Therefore, although the tsetse distribution created by TED model is similar to Ford's map (1971), the distribution of the tsetse flies still needs to be assessed with some field validation (DeVisser et al., 2010). This is clear with the Mount Kilimanjaro sites.

For the spreadsheet control cost model, the control costs were calculated under ideal situations. However, the potential tsetse reinvasion problem was not included in the model, which means the total costs for the elimination of tsetse flies might be underestimated (McCord et al., 2012). During the re-bait period, the inaccessibility of some remote areas might result in an overestimation of the control costs. (McCord et al., 2012). There may be some other overlooked costs, such as the overuse of water resources or fuel for vehicle, transaction costs, and impact of environmental damage. Transaction costs are linked with availability of the products in the market. For example, they could include the time and expense for finding the capital input when they are not available. Furthermore, the control method in the cost analysis under the study only included the traps and targets; however, in actual tsetse control operations, some diverse control methods, such as insecticide spraying, SIT, and ITC, might be integrated.

For the cost-benefit analysis, the populations inside suitable habitats for tsetse flies were all considered potential exposures, which was an obvious overestimation. There would be some suitable habitats not infested by tsetse flies, like Mount Kilimanjaro National Park and Kitulo Plateau National Park. There would also be some individuals limited by activity space to areas outside the tsetse habitat. Hence, the identification of the actual BCAs still needs assessment of both the presence of tsetse flies and population density inside these areas. In addition, given the lack of data to estimate the exact benefits in USD dollars, the benefits measured in this study were defined as the number of people who could benefit from the tsetse control activities. The cost-benefit analysis would be of interest to governments and fly management institutes, if the actual costs saved due to the elimination of tsetse flies were quantified and provided.

APPENDICES

APPENDIX A

Python Script for The Tsetse Ecological Distribution (TED) Model

The Tsetse Ecological Distribution (TED) Model

This Script is designed to be run in Python via command line, although you will need access to an ArcGIS license in order to run the ARCPY tools

The script is extremely dependent on file organization, although you can change the location of the TED Model directory folder below under 'User Defined Parameters'

The other file must be organized in the following manner:

TED_Model\\Fundamental_Niche_Outputs\\(The fundamental niche data will be written here)

TED_Model\\Land_Cover_Data\\ (classified land cover data for each year goes here - file must be named YEAR_Suitable_LC.tif)

TED_Model\\LST_Day_Data\\ (16-day composite day land surface temperature data goes here - file must be named YEAR_ORDINALDATE_LST_Day.tif)

TED_Model\\LST_Night_Data\\ (16-day composite night land surface temperature data goes here - file must be named YEAR_ORDINALDATE_LST_Night.tif)

TED_Model\\Model_Data\\(various temporary files will be written to this location, and the starting distribution data must be placed here   - the starting distribution must be named Start_Dist.tif)

TED_Model\\NDVI_Data\\(16-day composite NDVI data goes here - file must be named YEAR_ORDINALDATE_NDVI.tif)

TED_Model\\Realized_Niche_Outputs\\(The realized niche / tsetse distribution data will be written here, including the percent probability layer)

NOTE - the 2001 and 2002 data should be mean scene data (can be thought of as average daily) in order to ensure proper model initialization.

2001 and 2002 data should not be used for analysis purposes, thus is not permanently saved, and is not used in the creation of the percent probability layer.

```
print "The Tsetse Ecological Distribution (TED) Model is now running"
# Import system modules
import sys, string, os, arcinfo, arcgisscripting, arcpy, time

# Set Geoprocessing Environment
arcpy.CheckOutExtension("Spatial") #Once a script finished with an extension's tools, the function helps to return license
gp = arcgisscripting.create() # make the arcgisscriping work
arcpy.env.overwriteOutput = True # make sure the output could be overwritten
gp.cellSize = "250" # resolution is 250m

# User Defined Parameters:
# Location of the TED Model directory folder
# NOTE - it is recommended that the TED Model folder be placed directly on your C: drive (or equivalent) to minimize path names.
TED_Dir = "D:\\Yang_Anni\\TED_Model" # set directory
```

As a default, the fundamental niche data is not saved, however, by changing the "No" listed below to a "Yes" the environmental suitability data will be saved

NOTE - saving the fundamental niche data does increase model run time.

Produce_Fundamental_Niche = "No" # whether produce fundamental niche

Model Initialization: overestimation of 1st initialized, so at least one year should be run before

Current_Time = time.asctime(time.localtime(time.time())) # converts a tuple or struct_time representing a time as returned by gmtime() or localtime() to a 24-character string of the following form

Start_Time = Current_Time # make start time equals to current time

Starting_Distribution = TED_Dir + "\\Tanzania_Data\\Start_Dist.tif" # create start distribution with tsetse everywhere manually

Max_Expansion = TED_Dir + "\\Model_Data\\Max_Dist" # define Max_Expansion and create Max_Dist automatically

arcpy.CopyRaster_management(Starting_Distribution, Max_Expansion, "", "", "", "NONE", "NONE", "")# in case the start distribution be overwritten each time

Combined_Real_Niche = TED_Dir + "\\Model_Data\\Combined_RN" # define Combined_Real_Niche

arcpy.gp.Times_sa(Starting_Distribution, "0", Combined_Real_Niche) # make Combined_Real_Niche with no values in

if Produce_Fundamental_Niche == "Yes":

```
    Combined_Fund_Niche = TED_Dir + "\\Model_Data\\Combined_FN" # define
Combined_Fund_Niche
    arcpy.gp.Times_sa(Starting_Distribution, "0", Combined_Fund_Niche) # make
Combined_Fund_Niche with no values in
Year = 2001 # the year to start
Num_of_Scenes = 0 # Set the No. of the scenes
print "Modeling Environment Initialized"
print "Year / Ordinal Date of Completed Distribution Data:"


while Year < 9999:
    YearStr = str(Year)
    Date = 001
    while Date < 365:
        if Date == 1:     # change them into string to make them in order
            DateStr = "001"
        if Date == 17:
            DateStr = "017"
        if Date == 33:
            DateStr = "033"
        if Date == 49:
            DateStr = "049"
        if Date == 65:
```

```
        DateStr = "065"
    if Date == 81:
        DateStr = "081"
    if Date == 97:
        DateStr = "097"
    if Date >= 98:
        DateStr = str(Date)
    Year_Date = YearStr + "_" + DateStr # make it into "2001_001" format

    # Define Variables:
    NDVI = TED_Dir + "\\Tanzania_Data\\NDVI_Data\\" + Year_Date + ".tif"
    LST_Day = TED_Dir + "\\Tanzania_Data\\LST_Day_Data\\" + Year_Date +
"_Day_LST_1km_Terra_16day.tif"
    LST_Night = TED_Dir + "\\Tanzania_Data\\LST_Night_Data\\" + Year_Date +
"_Night_LST_1km_Terra_16day.tif"
    NDVI_RC = TED_Dir + "\\Model_Data\\NDVI_RC"
    LST_Day_RC = TED_Dir + "\\Model_Data\\LST_Day_RC"
    LST_Night_RC = TED_Dir + "\\Model_Data\\LST_Night_RC"
    MODIS_LC_RC = TED_Dir + "\\Tanzania_Data\\Land_Cover_Data\\" + YearStr +
"_Tsetse_RC.tif"
    LST_Suit = TED_Dir + "\\Model_Data\\LST_Suit"
    Climate_Suit = TED_Dir + "\\Model_Data\\Climate_Suit"
```

```
Total_Suit = TED_Dir + "\\Model_Data\\Total_Suit"

Real_Niche = TED_Dir + "\\Model_Data\\Real_Niche"

Realized_Niche = TED_Dir + "\\Realized_Niche_Outputs\\" + Year_Date +
"_Realized_Niche.tif"

Combined_Real_Niche_temp = TED_Dir + "\\Model_Data\\CRN_temp"

Fundamental_Niche = TED_Dir +
"\\Tanzania_Data\\Fundamental_Niche_Outputs\\" + Year_Date + "_Fundamental_Niche.tif"

Combined_Fund_Niche_temp = TED_Dir + "\\Model_Data\\CFN_temp"


if arcpy.Exists (NDVI):

    #Processing Steps:

    # Reclassify NDVI

    arcpy.gp.Reclassify_sa(NDVI, "Value", "-3 0.39 0;0.39 3 1", NDVI_RC,
"DATA") # make ndvi<0.39 equals 0, otherwise equals 1

    # Reclassify Day LST

    arcpy.gp.Reclassify_sa(LST_Day, "Value", "-30 17 0;17 40 1;40 100 0",
LST_Day_RC, "DATA") # make day tem<17 equals 0, otherwise equals 1

    # Reclassify Night LST

    arcpy.gp.Reclassify_sa(LST_Night, "Value", "-30 10 0;10 40 1;40 100 0",
LST_Night_RC, "DATA") # make night tem<10 equals 0, otherwise equals 1

    # Calculate Fundamental Niche
```

arcpy.gp.Times_sa(LST_Day_RC, LST_Night_RC, LST_Suit) # get the suitable temperature

arcpy.gp.Times_sa(NDVI_RC, LST_Suit, Climate_Suit) # get the suitable climate

arcpy.gp.Times_sa(Climate_Suit, MODIS_LC_RC, Total_Suit) # get the suitable habitat

if Produce_Fundamental_Niche == "Yes":

arcpy.CopyRaster_management(Total_Suit, Fundamental_Niche, "", "", "", "NONE", "NONE", "") # make the suitable habitat as fund_niche

Calculate Realized Niche

arcpy.gp.Times_sa(Total_Suit, Max_Expansion, Realized_Niche) # combine fund_niche with fly movement to get real_niche

Expand Distributions

arcpy.gp.Expand_sa(Realized_Niche, Max_Expansion, "2", "1") # expand 2 cells around the real_niche

if Year <= 2002: # delete initialization output

arcpy.Delete_management(Realized_Niche)

if Produce_Fundamental_Niche == "Yes":

arcpy.Delete_management(Fundamental_Niche)

else:

```
            # Combine Distributions
            arcpy.gp.Plus_sa(Combined_Real_Niche, Realized_Niche,
Combined_Real_Niche_temp) # add the current distribution to previous ones
            arcpy.CopyRaster_management(Combined_Real_Niche_temp,
Combined_Real_Niche, "", "", "", "NONE", "NONE", "") # copy temporary one to the output
            if Produce_Fundamental_Niche == "Yes":
                arcpy.gp.Plus_sa(Combined_Fund_Niche, Fundamental_Niche,
Combined_Fund_Niche_temp) # add the current distribution to previous ones
                arcpy.CopyRaster_management(Combined_Fund_Niche_temp,
Combined_Fund_Niche, "", "", "", "NONE", "NONE", "") # copy temporary one to the
output
            Num_of_Scenes = Num_of_Scenes + 1

        print Year_Date
        Date = Date + 16

    else:
        print "End of Input Data"
        print "Number of Scenes Produced: ", Num_of_Scenes
        print "Finalizing Model Outputs"
        # Calculate Percent Probability Layer
        Date = Date - 16
```

```
if Date == -15:
    DateStr = "353"
    Year = Year - 1
    YearStr = str(Year)
if Date == 1:
    DateStr = "001"
if Date == 17:
    DateStr = "017"
if Date == 33:
    DateStr = "033"
if Date == 49:
    DateStr = "049"
if Date == 65:
    DateStr = "065"
if Date == 81:
    DateStr = "081"
if Date == 97:
    DateStr = "097"
if Date >= 98:
    DateStr = str(Date)
Year_Date = YearStr + "_" + DateStr
# define Real_Niche_Percent_Probaility
```

```
			Real_Niche_Percent_Probability = TED_Dir +
"\\Tanzania_Data\\Realized_Niche_Outputs\\Real_Niche_Prob_2003_001_to_" + Year_Date
+ ".tif"
			arcpy.CopyRaster_management(Combined_Real_Niche,
Combined_Real_Niche_temp, "", "", "-1", "NONE", "NONE", "32_BIT_FLOAT")
			# real_niche/No.of scences
			arcpy.gp.Divide_sa(Combined_Real_Niche_temp, Num_of_Scenes,
Real_Niche_Percent_Probability)
			if Produce_Fundamental_Niche == "Yes":
				Fund_Niche_Percent_Probability = TED_Dir +
"\\Tanzania_Data\\Fundamental_Niche_Outputs\\Fund_Niche_Prob_2003_001_to_" +
Year_Date + ".tif"
				arcpy.CopyRaster_management(Combined_Fund_Niche,
Combined_Fund_Niche_temp, "", "", "-1", "NONE", "NONE", "32_BIT_FLOAT")
				arcpy.gp.Divide_sa(Combined_Fund_Niche_temp, Num_of_Scenes,
Fund_Niche_Percent_Probability)
			print "Percent Probability of Tsetse Presence Between 2003_001 and " +
Year_Date + " Calculated"
			Date = 366
			Year = 99998

	Year = Year + 1
```

```
# Delete unnecessary files and temporary files
arcpy.Delete_management(NDVI_RC)
arcpy.Delete_management(LST_Day_RC)
arcpy.Delete_management(LST_Night_RC)
arcpy.Delete_management(LST_Suit)
arcpy.Delete_management(Climate_Suit)
arcpy.Delete_management(Total_Suit)
arcpy.Delete_management(Max_Expansion)
arcpy.Delete_management(Combined_Real_Niche)
arcpy.Delete_management(Combined_Real_Niche_temp)
arcpy.Delete_management(Combined_Fund_Niche)
arcpy.Delete_management(Combined_Fund_Niche_temp)


Completion_Time = time.asctime( time.localtime(time.time()) )
print "The Tsetse Ecological Model has finished"
print "Start Time: ", Start_Time
print "Completion Time: ", Completion_Time
```

APPENDIX B

R Script for Kernel Density Estimation (KDE) to Identify Hot Spots

```
# import R packages
library(sp)
library(rgdal)
library(maps)
library(spatstat)
library(splancs)
library(rgdal)
library(maptools)
library(GISTools)

#Set work directory and read the .csv file
setwd("F:/Dropbox")
data=read.csv("data_xy.csv")

#Project the data and plot the points
coordinates(data)=c("x","y")
proj4string(data) = CRS("+proj=longlat +ellps=WGS84 +datum=WGS84")
peq = spTransform(data, CRS("+proj=utm +zone=37 +datum=WGS84"))
summary(peq)
plot(peq,cex=0.5,pch=19)

#Get Tanzania boundaries from maps library
```

```
ctydat<-map('world', region='tanzania', fill=TRUE, col="transparent", plot=FALSE)

#Project Tanzania boundaries
ctydat<- map2SpatialPolygons(ctydat, ctydat$names, proj4string=CRS("+proj=longlat
+datum=WGS84"))
ctydat = spTransform(ctydat, CRS("+proj=utm +zone=37 +datum=WGS84"))
plot(ctydat, lty=1, add=T)
title(main="Interesting Areas (Pop_Den>1000 & Tse_Pre>0.52)",)

#convert to class "ppp"
summary(peq@coords)
xys<-peq@coords
eqs_spp<- ppp(xys[,1],xys[,2], c(-550000, 700000), c(-1300000, -110000),
unitname=c("metres","metres") )

#get optimal bandwidth using Diggle's function (1985)
diggle.bw=bw.diggle(eqs_spp)
print(diggle.bw)
plot(diggle.bw)

#make KDE map and let bandwidth equals to optimal bandwidth
bw=diggle.bw
```

```
plot(density(eqs_spp, sigma=bw), col=terrain.colors(10), main=paste("Hot Spot of
Beneficial Control Areas, bw=", bw),par=20)
map.scale(x=-380000, y=-1180000,len=100000,ndivs = 1,units="Kilometer" )
north.arrow(xb=-500000,yb=-1150000,len=20000,lab="")

#Identification of Point Patterns by Ghat, Fhat, Khat, and Lhat for validation (This part is
not shown in manuscript)
#Ghat & Fhat
g.mp <- Gest(eqs_spp, correction=c('km'))
f.mp <- Fest(eqs_spp, correction=c('km'))

plot(g.mp$r, g.mp$km, type='l', col='green4', main="BCAs: Nearest Neighbor
Distances", xlab='Distance', ylab='Proportion')
lines(g.mp$r, g.mp$theo, lty=3, col='purple', add=TRUE)
lines(f.mp$r, f.mp$km, col='red', lty=2)
legend(8000,0.3, legend=c('event-event', 'random (Poisson)', 'point-event'), lty=c(1,3,2),
col=c('green4', 'purple', 'red'))

#Khat
k.mp <- Kest(eqs_spp, correction='translate')
plot(k.mp, main="BCAs: Ripley's Reduced 2nd Moment Function")
```

```
#Lhat

l.mp <- Lest(eqs_spp, correction='translate')

plot(l.mp, main="BCAs: L-hat")

plot(l.mp$r, (l.mp$trans-l.mp$r), type='l', xlab='r (h)', ylab='L-hat-h',
main="Mid-Michigan Places : L-hat - h")

abline(h=0, col='purple', lty=3)
```

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